The physics programme of the ALICE experiment at the LHC

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- Nucleus-nucleus collisions (and p-p) at the LHC
- The ALICE experiment
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- Highlights on some physics topics *
  - ❑ Soft physics I
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Lecture 1

  - ❑ Soft physics II
    - ➢ strange baryons and elliptic flow
  - ❑ Heavy Flavours and quarkonia
  - ❑ Jets
- Conclusions

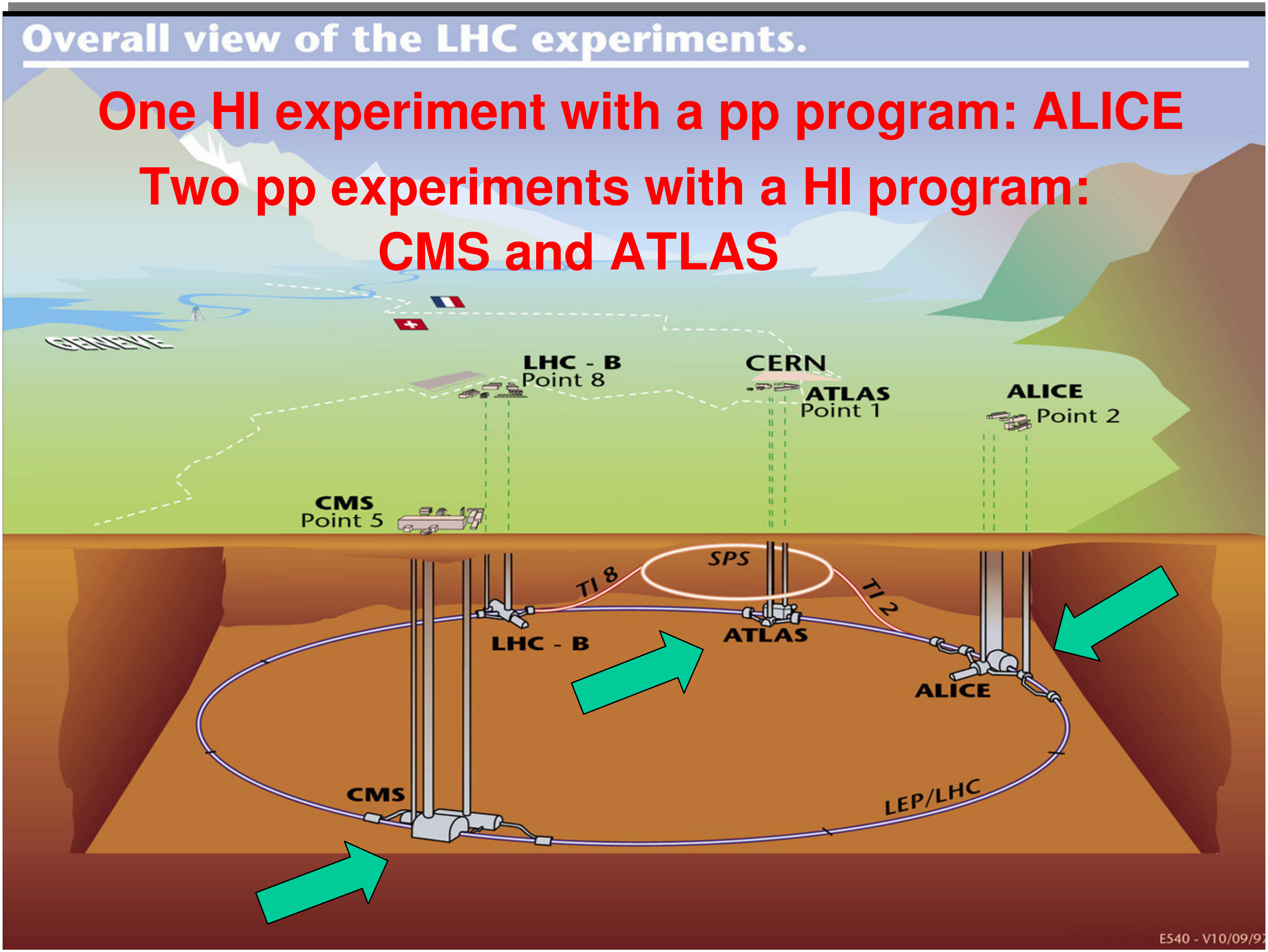
Lecture 2

* Results of studies published on Physics Performance Report Vol.II, CERN/LHCC 2005-030

Nucleus-nucleus (and pp) collisions at the LHC

One HI experiment with a pp program: ALICE

Two pp experiments with a HI program: CMS and ATLAS



The beams at the LHC machine

Running parameters:

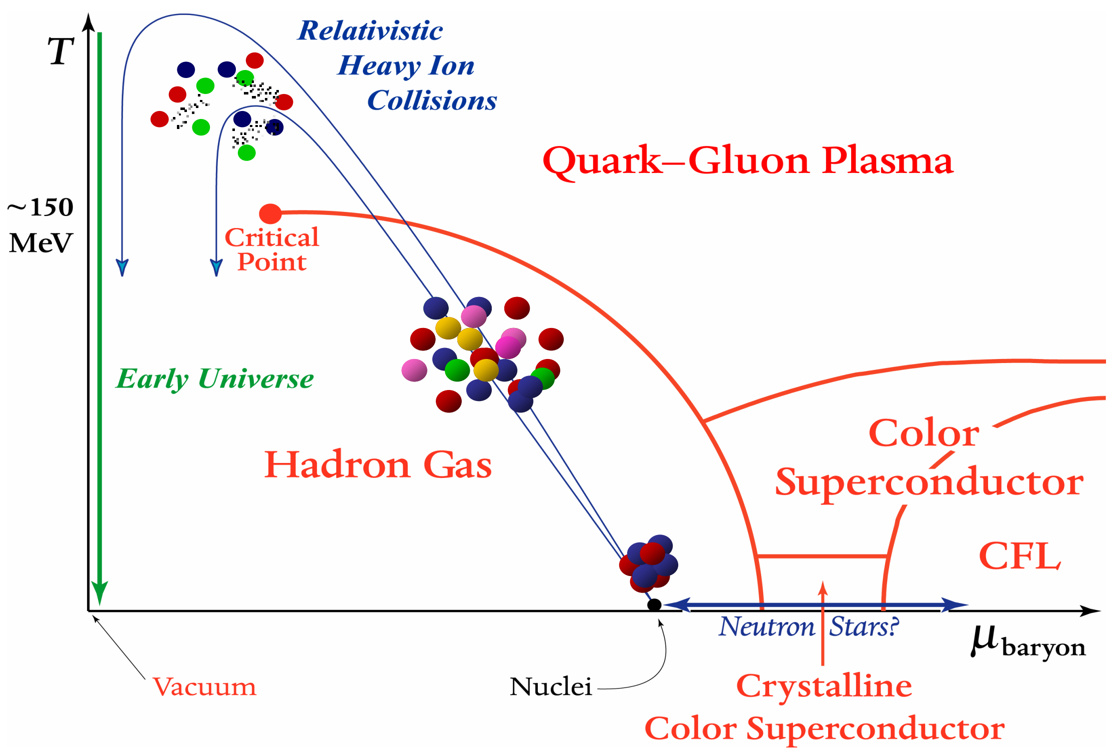
Collision system	$\sqrt{s_{NN}}$ (TeV)	$\mathcal{L}_0$ ($cm^{-2}s^{-1}$)	$<\mathcal{L}>/\mathcal{L}_0$ (%)	Run time (s/year)	σ_{geom} (b)
pp	14.0	10^{34} *		10^7	0.07
PbPb	5.5	10^{27}	70-50	10^6 **	7.7

* $\mathcal{L}_{max}$(ALICE) = 10^{31} ** $\mathcal{L}_{int}$(ALICE) ~ 0.7 nb^{-1}/year

Then, other collision systems:
pA, lighter ions (Sn, Kr, Ar, O)
and lower energies (pp @ 5.5 TeV)

Why heavy ion collisions: the QCD phase diagram

Colliding two heavy nuclei at ultrarelativistic energies allows to create in the laboratory a bulk system with huge density, pressure and temperature (T over 100,000 times higher than in the core of the Sun) and to study its properties.



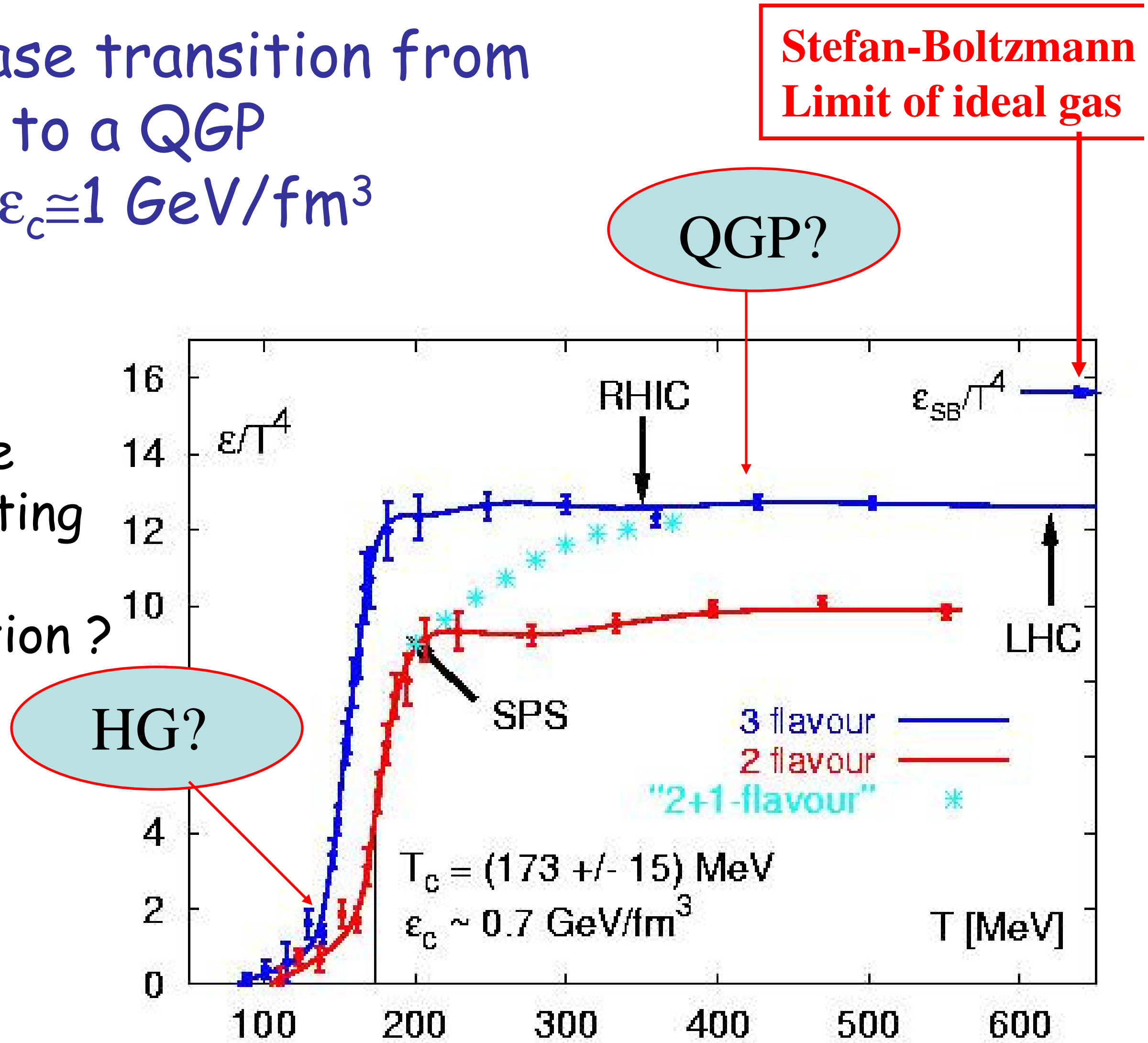
QCD predicts that under such conditions a phase transition from a system composed of colorless hadrons to a Quark Gluon Plasma (QGP) should occur (the QGP should live for a very short time, about 10^{-23}s, or a few fm/c).

Lattice QCD calculations

Indication of phase transition from
Hadron gas (HG) to a QGP
at $T_c \cong 170$ MeV $\varepsilon_c \cong 1$ GeV/fm^3

- true phase transition or crossover?
- free QGP or intermediate phase of strongly interacting QGP (sQGP) ?
- Chiral symmetry restoration ?

$m_u = m_d = m_s$
$m_u = m_d$
$m_u = m_d$; $m_s > m_{u,d}$



F.Karsch, E.Laermann and A.Peikert, Phys. Lett. B478 (2000) 447.

New conditions created at the LHC

Central collisions	SPS	RHIC	LHC
$s^{1/2}$(GeV)	17	200	5500
dN_{ch}/dy	500	850	*1500-3000*
ε (GeV/fm^3)	2.5	4–5	*15–40*
V_f(fm^3)	10^3	7×10^3	*2×10^4*
τ_{QGP} (fm/c)	<1	1.5–4.0	*4–10*
τ_0 (fm/c)	~1	~0.5	*<0.2*

Formation time τ_0 — 3 times shorter than RHIC
Lifetime of QGP τ_{QGP} — factor 3 longer than RHIC
Initial energy density ε_0 — 3-10 higher than RHIC

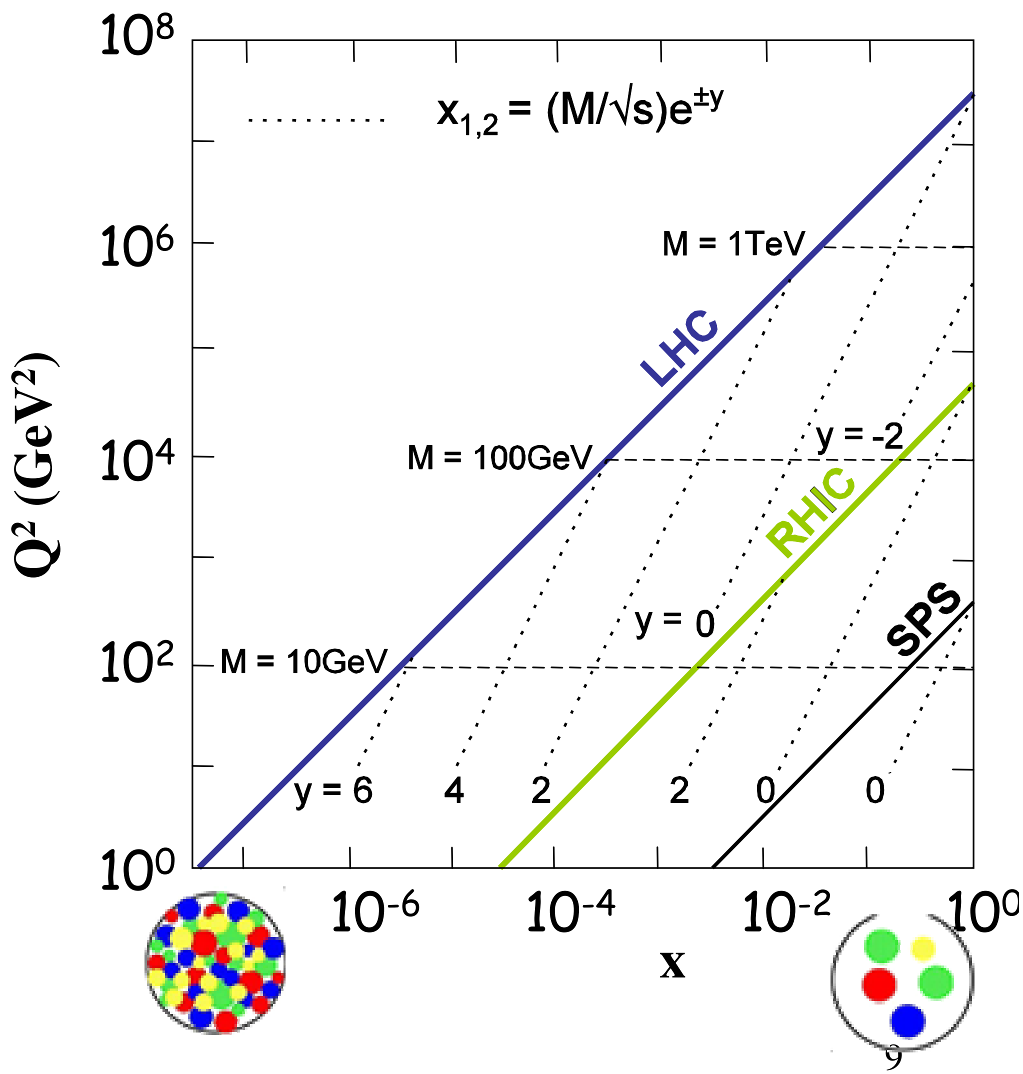
A new kinematic regime

Probe initial partonic state in a new Bjorken-x range (10^{-3}-10^{-5}):

- nuclear shadowing,
- high-density saturated gluon distribution.

Larger saturation scale (Q_S=0.2$A^{1/6}$ $\sqrt{s}^{\delta}$= 2.7 GeV): **particle production dominated by the saturation region.**

The QGP at LHC might evolve from a **Color Glass Condensate** in the initial state of the collision.



... and more hard processes

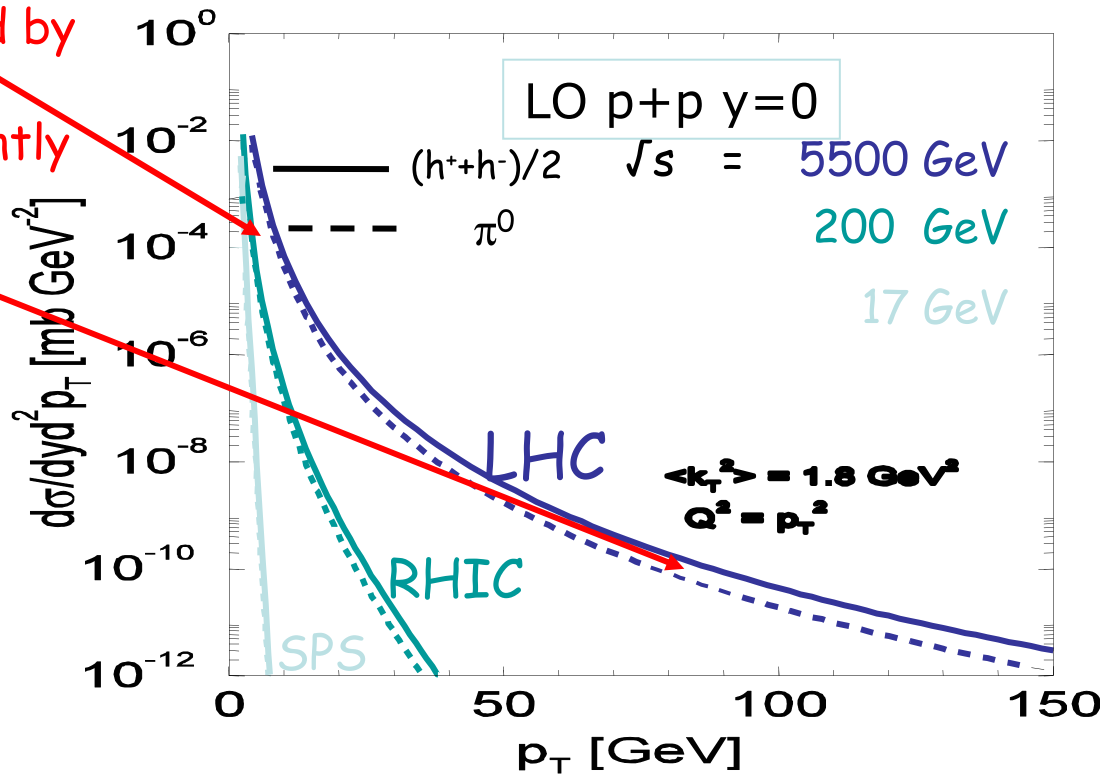
LHC: $\sigma_{hard}/\sigma_{total}$ = 98% (50% at RHIC)

At LHC hard processes contribute significantly to the total AA cross-section.

- Bulk properties are dominated by hard processes
- Very hard probes are abundantly produced.

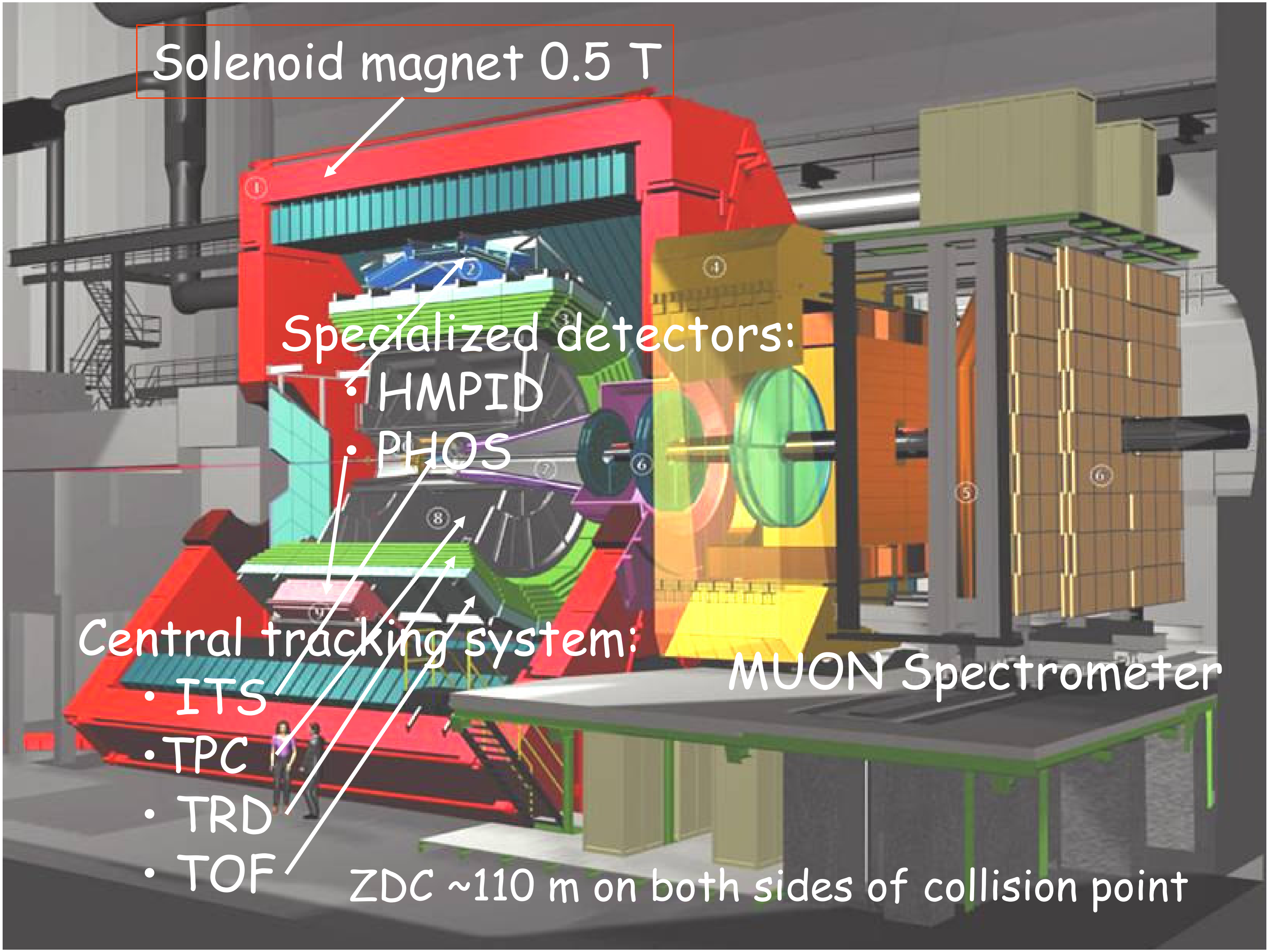
Hard processes are extremely useful tools:

- Probe matter at very early times.
- Hard processes can be calculated by pQCD



Heavy quarks and weakly interacting probes become accessible

The ALICE experiment

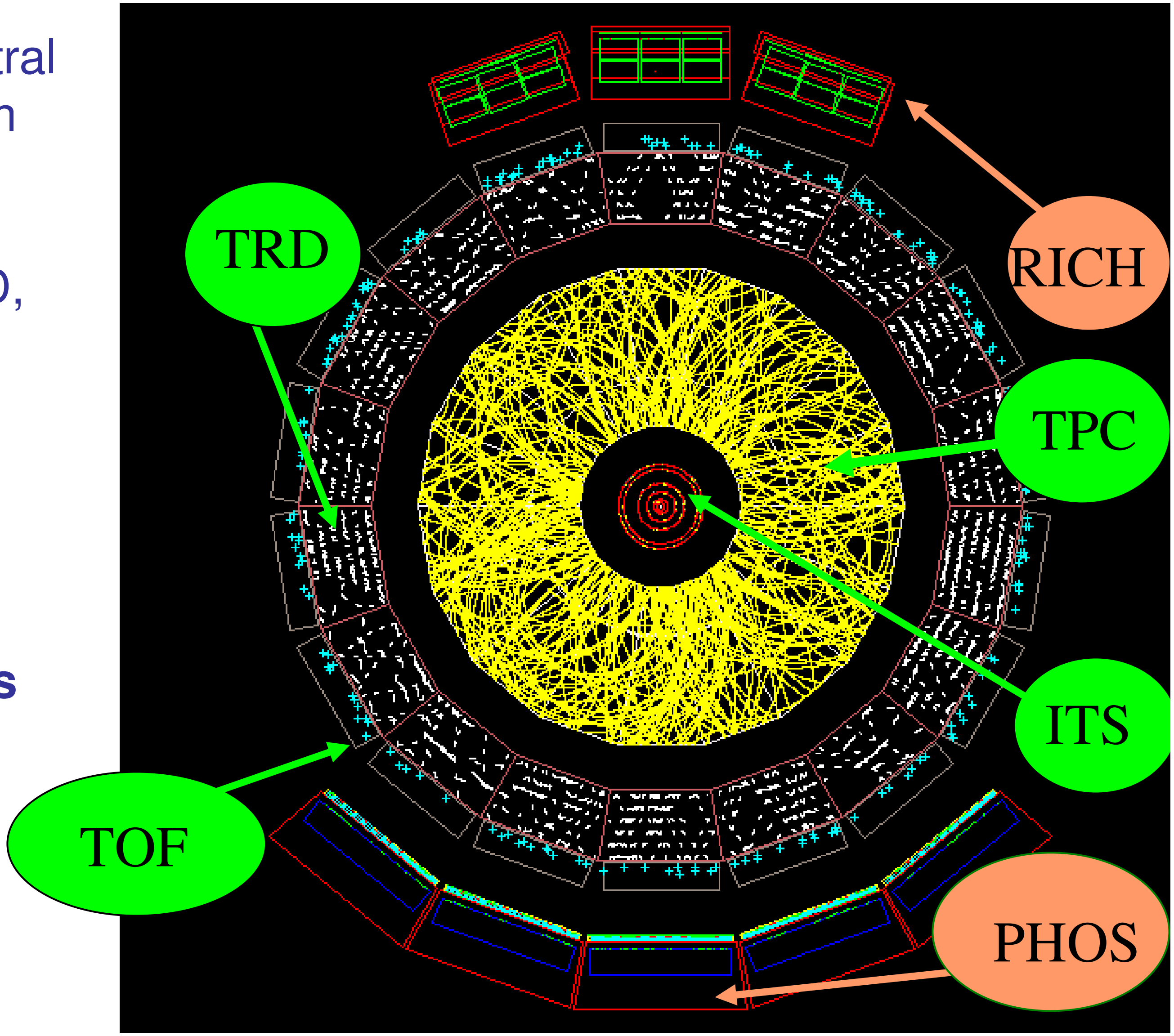


Solenoid magnet 0.5 T
Specialized detectors:
• HMPID
• PHOS
Central tracking system:
• ITS
• TPC
• TRD
• TOF
MUON Spectrometer
ZDC ~110 m on both sides of collision point

Tracking: the major challenge for ALICE

- Event display for a central Pb-Pb collision as seen in ALICE.
- Tracking in the central barrel involves TOF, TRD, TPC, ITS.

- $N_{ch}(-0.5<\eta<0.5)=8000$
- **Only a slice of $\Delta\theta=2^o$ is shown**



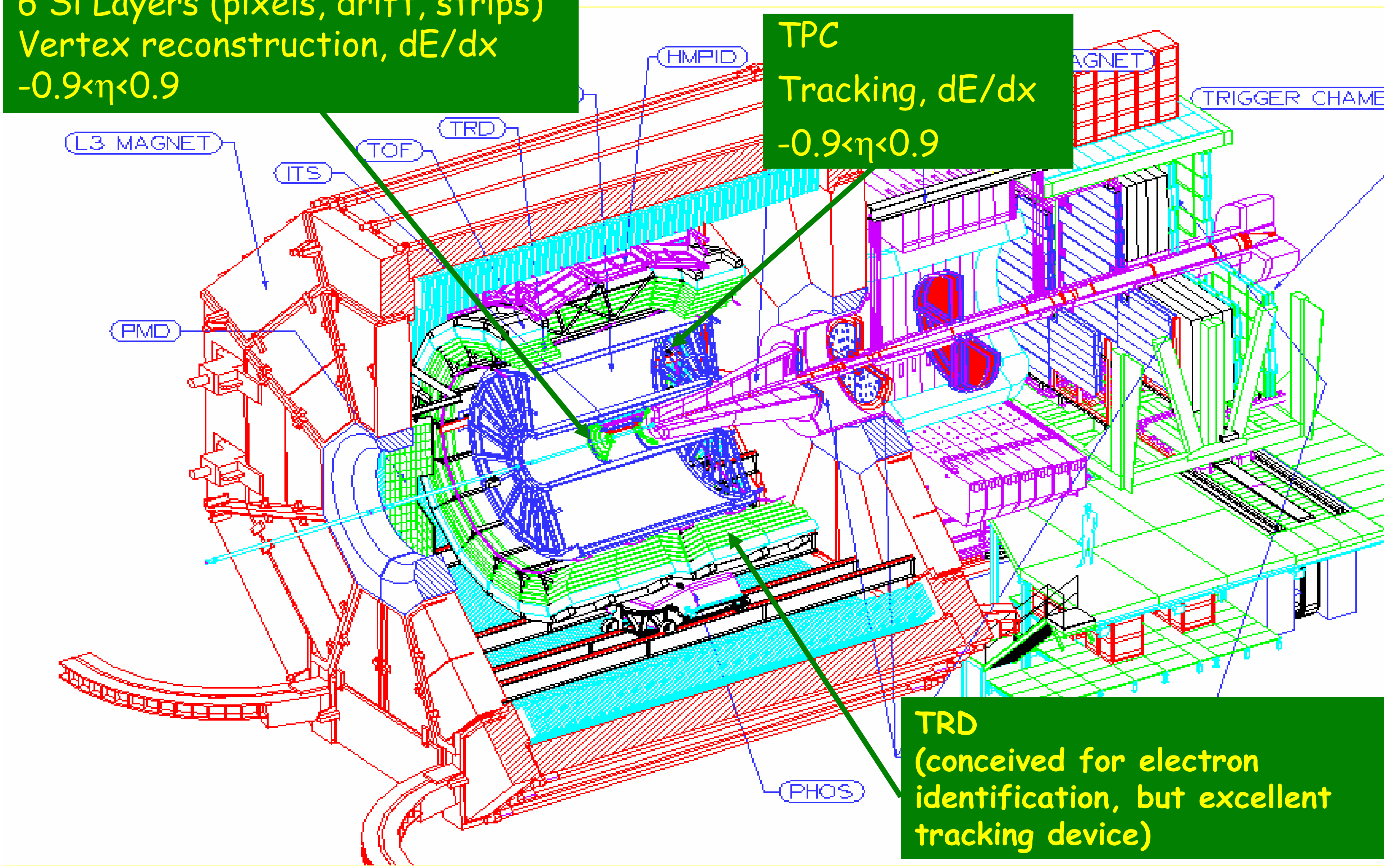
ALICE layout : tracking

Inner Tracking System (ITS):
6 Si Layers (pixels, drift, strips)
Vertex reconstruction, dE/dx
$-0.9<\eta<0.9$

TPC

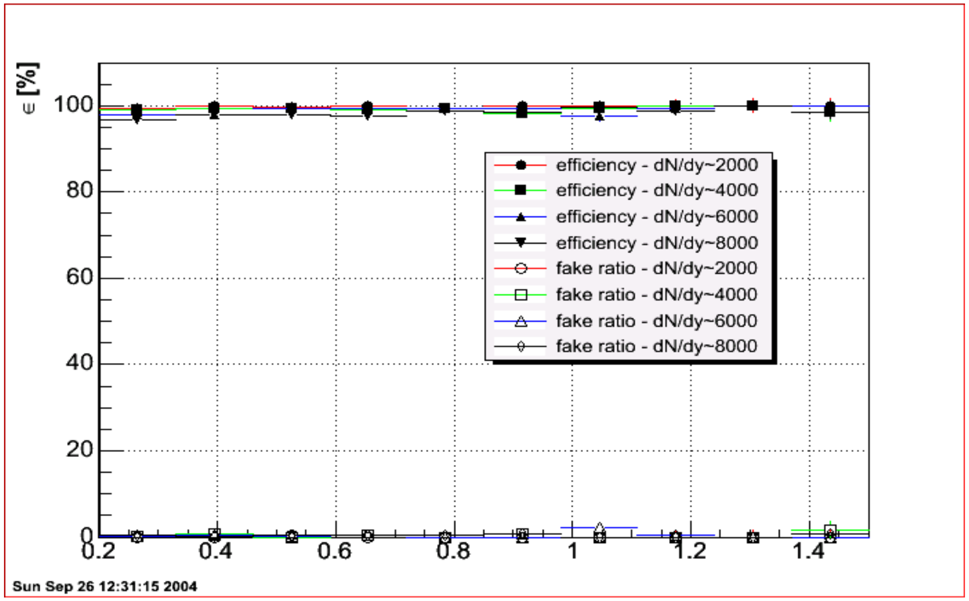
Tracking, dE/dx

$-0.9<\eta<0.9$



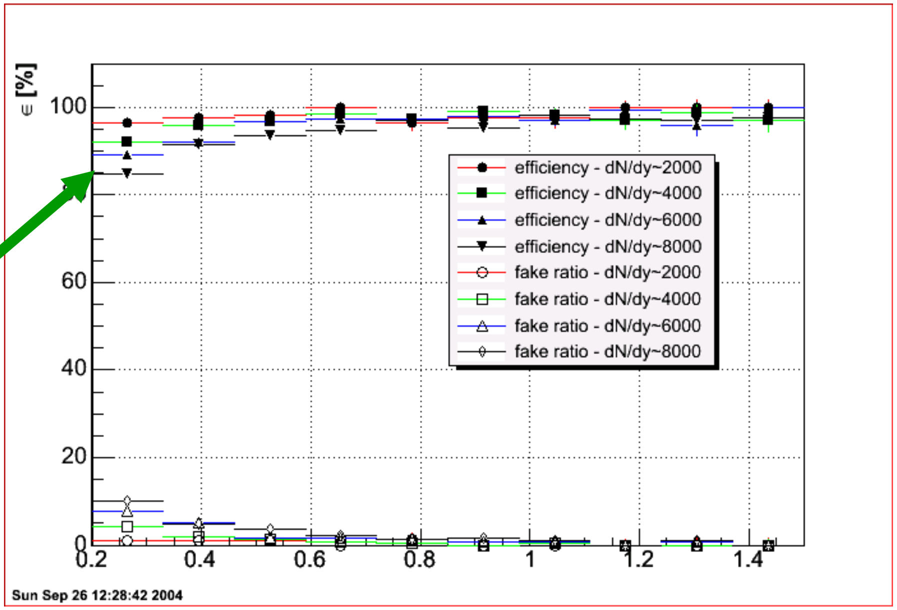
TRD
(conceived for electron identification, but excellent tracking device)

Tracking efficiency



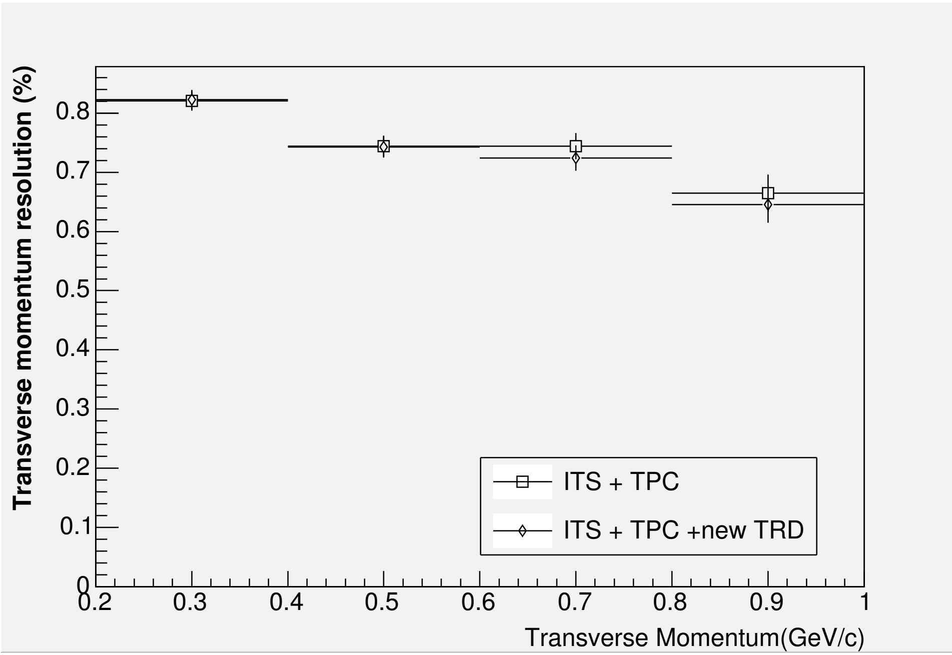
TPC

ITS+TPC+TOF+TRD



Good efficiency down to very low p_T !!!

Combined momentum resolution



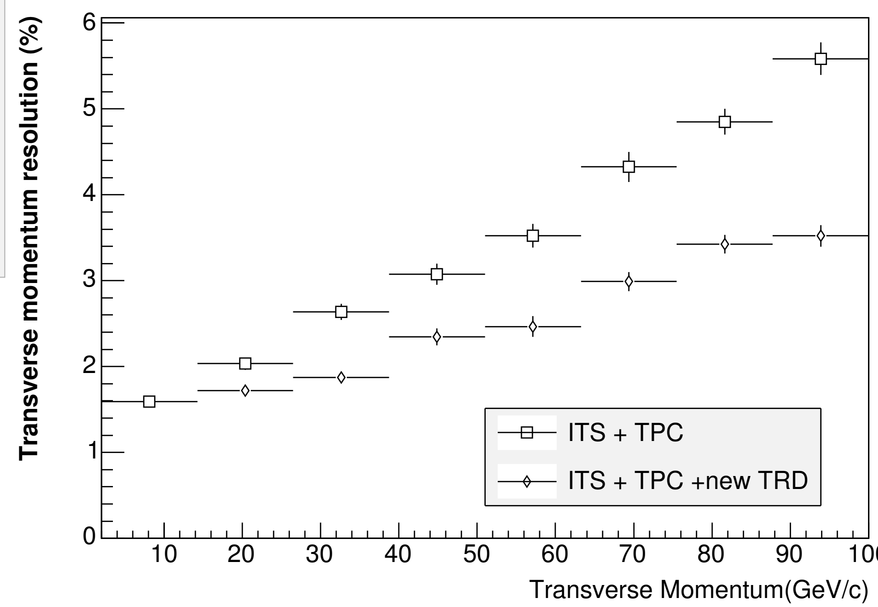
at low momentum dominated by

- **ionization-loss fluctuations**
- **multiple scattering**

at high momentum determined by

- **point measurement precision**
- **alignment & calibration**

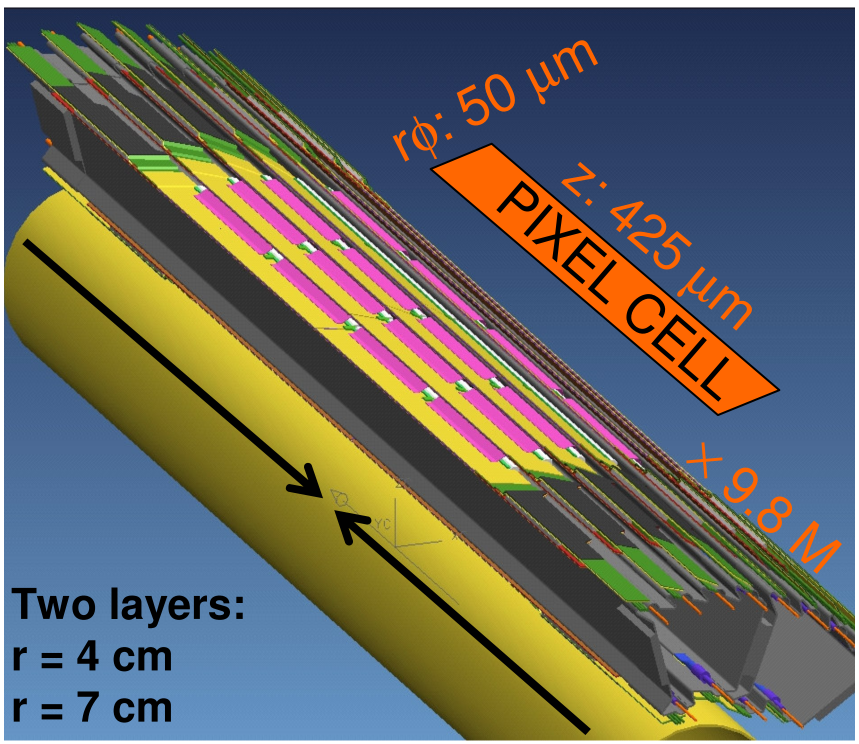
(*assumed ideal here*)

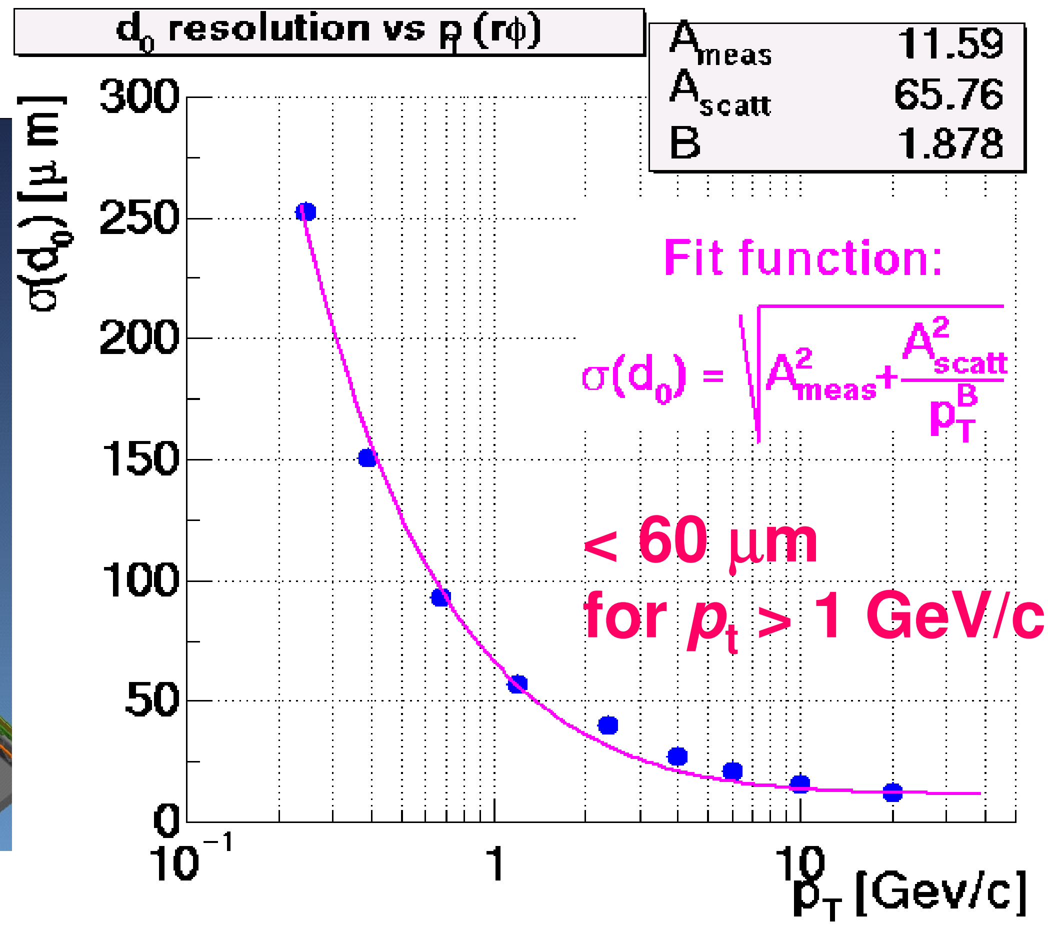


resolution ~ 4 % at 100 GeV/c
excellent performance in hard region!

Track impact parameter resolution

- It is crucial for the reconstruction of secondary vertices (identification of particles from their decay topology)
- Mainly provided by the 2 innermost layers (pixel cells) in the silicon central tracker (ITS = Inner Tracking System)





ALICE: an ideal soft particle tracker

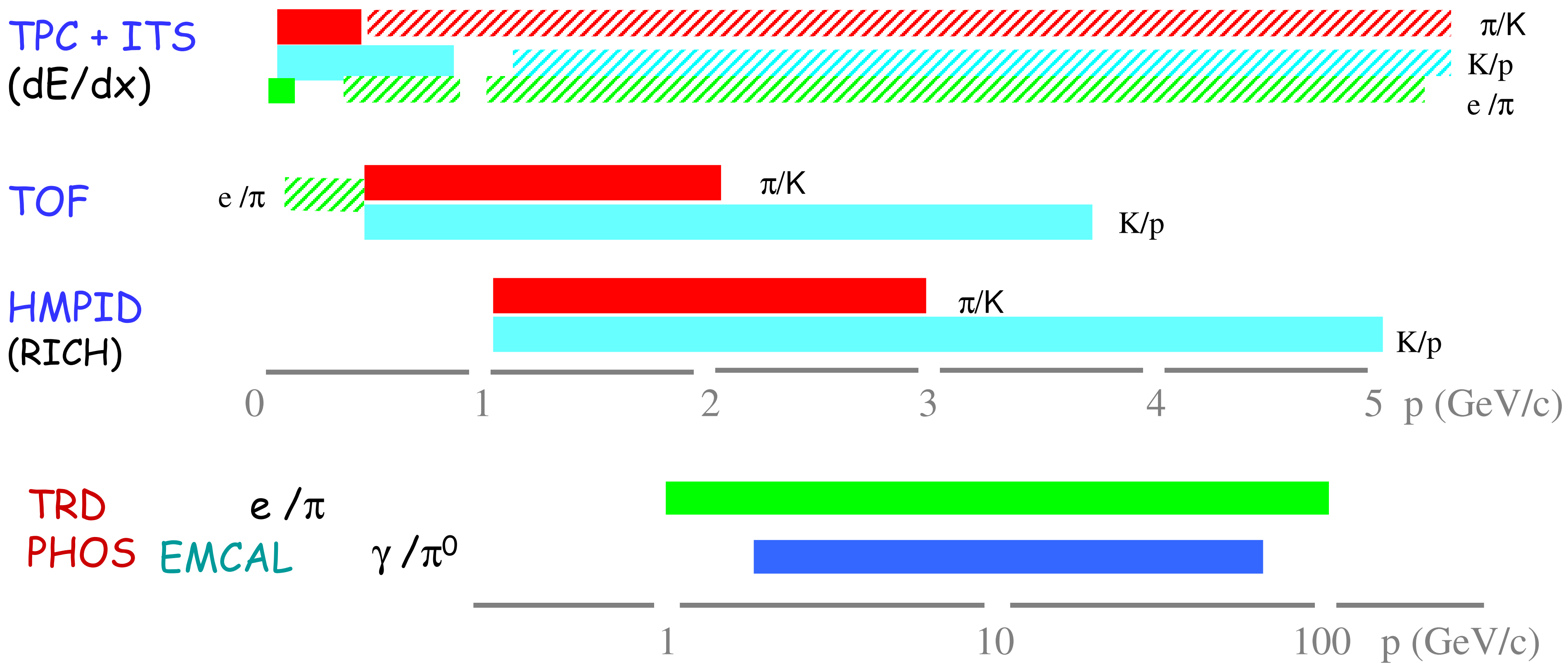
- ALICE is sensitive down to very low P_T

	Magnetic field (T)	P_T cutoff (GeV/c)	Material thickness: X/X_0 (%)
ALICE	0.5	0.15	7
ATLAS	2.0	0.5	30
CMS	4.0	0.75	20
LHCb	4Tm	0.1*	3.2

- Moreover ALICE has remarkable capabilities of particle identification

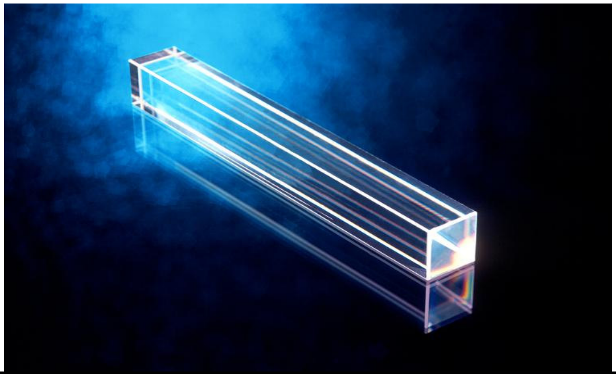
ALICE Particle Identification

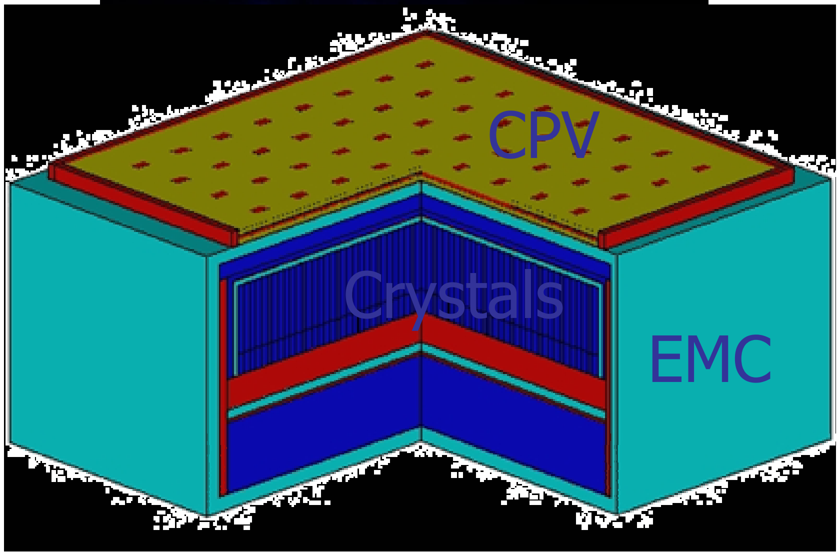
Alice uses ~ all known techniques!



PHOton Spectrometer: PHOS

High resolution spectrometer



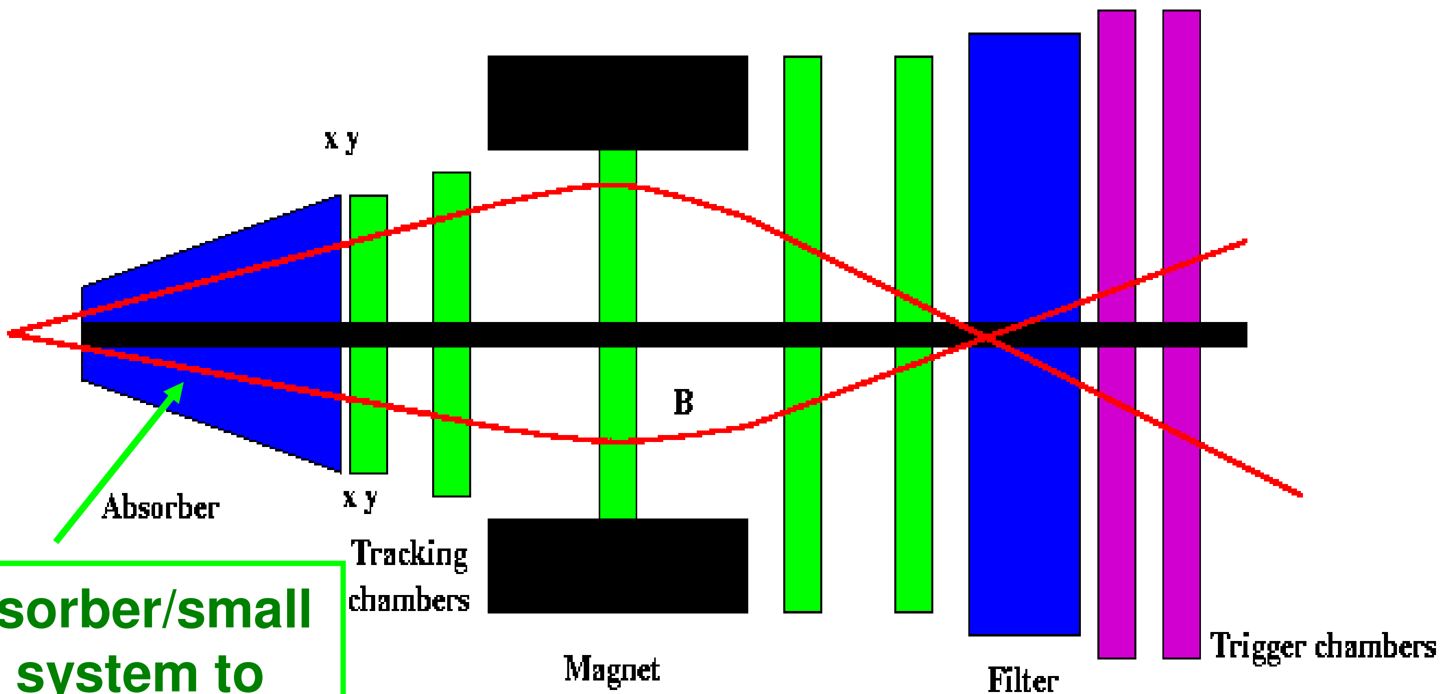


- High granularity detector:
  - 17920 lead-tungstate crystals ($PbWO_4$), 5 modules (56×64)
  - crystal size: 22 × 22 × 180 mm^3
  - depth in radiation length: 20
- Distance to IP: 4.4 m
- Acceptance:
  - pseudo-rapidity [-0.12,0.12]
  - azimuthal angle 100°
- **Energy resolution ~ 3% / √ E**
- **Dynamic range from ~ 100 MeV to ~ 100 GeV**
- **Timing resolution of ~ 1.5 ns / √ E**
- **Trigger capability at first level**

- Charged Particle Veto, CPV
  - multi-wire particle gas chamber

Dimuon Spectrometer

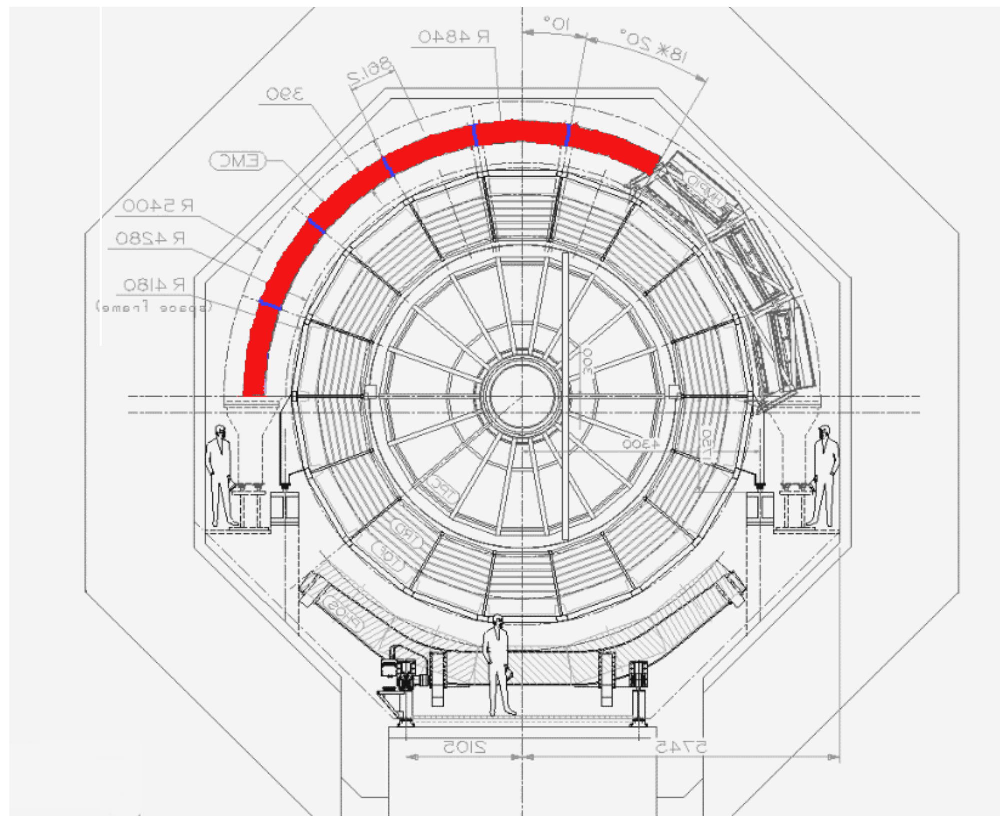
- Study the production of the J/Ψ, Ψ', ϒ, ϒ' and ϒ'' decaying in 2 muons, $2.5 < \eta < 4$
- Resolution of 70 MeV at the J/Ψ and 100 MeV at the ϒ



Complex absorber/small angle shield system to minimize background (90 cm from vertex)

Proposed ALICE EMCAL

- **EM Sampling Calorimeter (STAR Design)**
- **Pb-scintillator linear response**
  - **$-0.7 < \eta < 0.7$**
  - $60° < \Phi < 180°$
- **Energy resolution $\sim 15\%/\sqrt{E}$**



Summary of the ALICE features

With its system of detectors ALICE will meet the challenge to measure event-by-event the flavour content and the phase-space distribution of highly populated events produced by heavy ion collisions:

- Most (2π * 1.8 units of η) of the hadrons (dE/dx + TOF), leptons (dE/dx, transition radiation, magnetic analysis) and photons (high resolution EM calorimetry).

- Track and identify from very low p_t (~ 100 MeV/c; soft processes) up to very high p_t (>100 GeV/c; hard processes).

- Identify short lived particles (hyperons, D/B meson) through secondary vertex detection.

- Identify jets.

p_t coverage: ALICE vs CMS and ATLAS

0 1 2 10 100

$T=\Lambda_{QCD}$ Q_s p_t (GeV/c)

Bulk properties

Hard processes modified by the medium

ALICE

PID

CMS&ATLAS

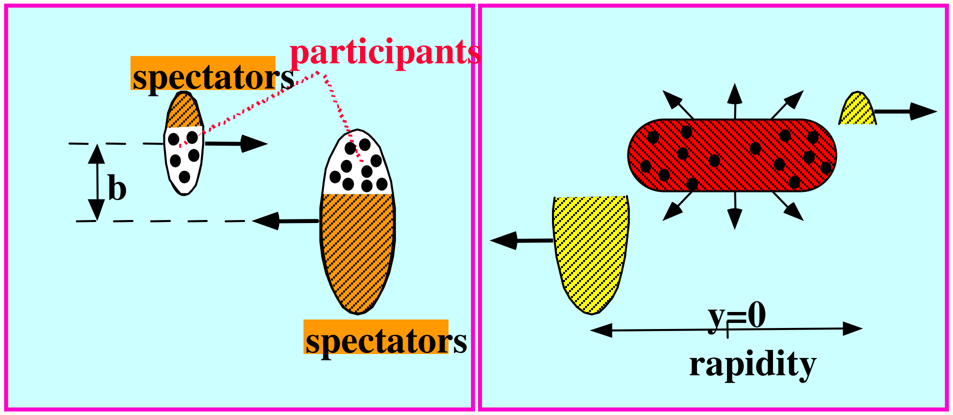
ALICE Physics Goals

- Event characterization in the new energy domain (for PbPb but also for pp)
  - multiplicity, η distributions, centrality
- Bulk properties of the hot and dense medium, dynamics of hadronization
  - chemical composition, hadron ratios and spectra, dilepton continuum, direct photons
- Expansion dynamics, space-time structure
  - radial and anisotropic flow, momentum (HBT) correlations
- Deconfinement:
  - charmonium and bottomonium spectroscopy
- Energy loss of partons in quark gluon plasma:
  - jet quenching, high p_t spectra
  - open charm and open beauty
- Chiral symmetry restoration:
  - neutral to charged ratios
  - resonance decays
- Fluctuation phenomena, critical behavior:
  - event-by-event particle composition and spectra

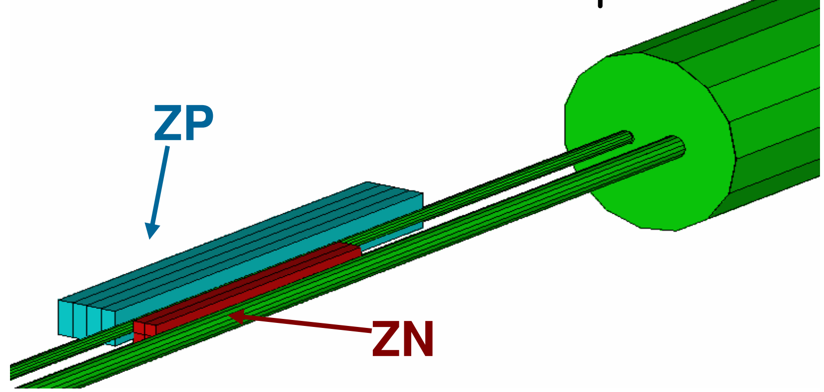
Not covered by these lectures

Event characterization in ALICE

ZDC and centrality determination



~100 m from interaction point



We measure in the ZDC for each event the energy carried by spectators (individual neutrons, protons and fragments)

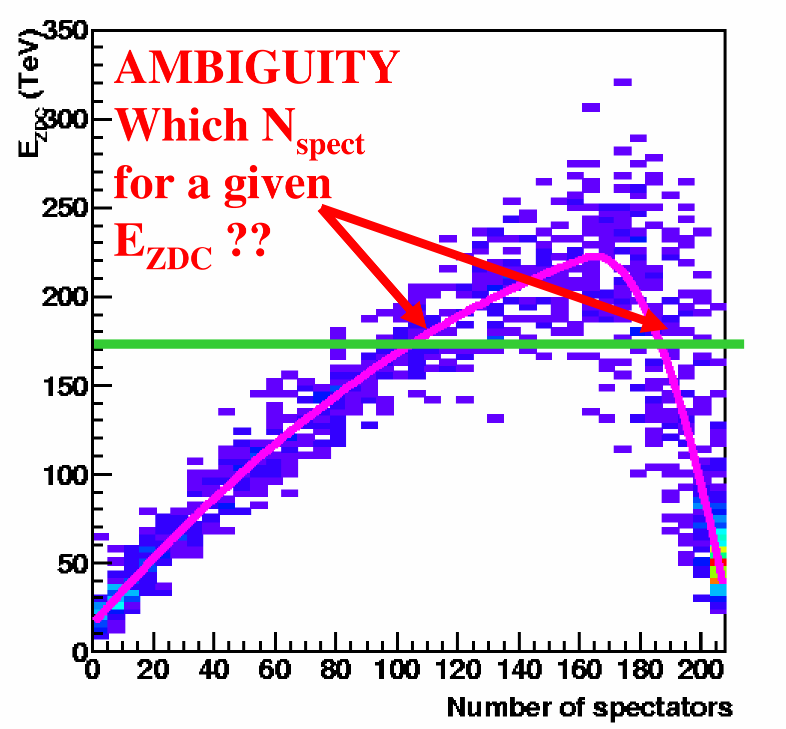
If we can determine from it the number of projectile spectators N_{spect}, then :

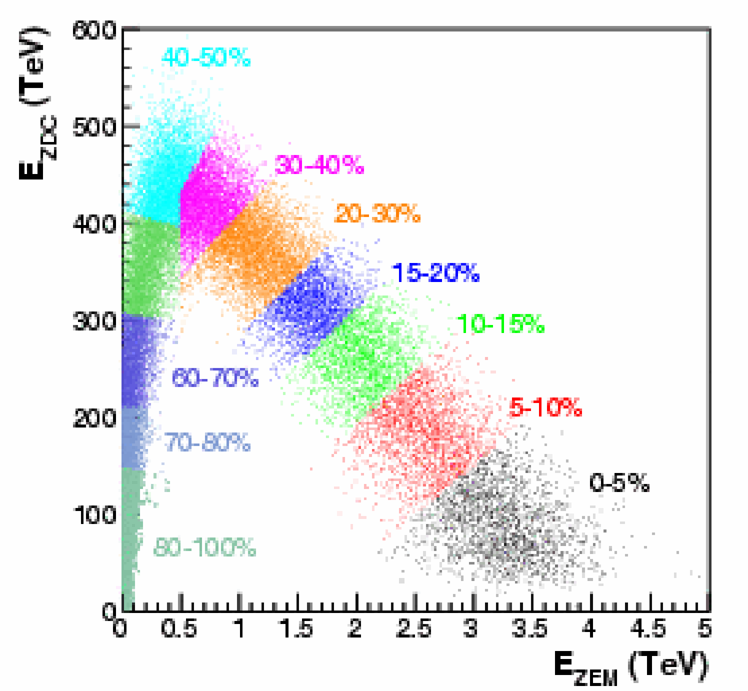
$N_{part} = A - N_{spect}$ centrality estimate

Then, with a Glauber superposition model, N_{part} can be converted to b, or to % of inelastic cross section.

ZDC + ZEM for centrality determination

- E_{ZDC} correlated with number of spectators BUT two branches in the correlation
  - Break-up of correlation due to production fragments (mainly in peripheral collisions)
- An additional calorimeter (ZEM = Zero Electromagnetic Calorimeter) at 7m from interaction point, is used to solve the ambiguity.





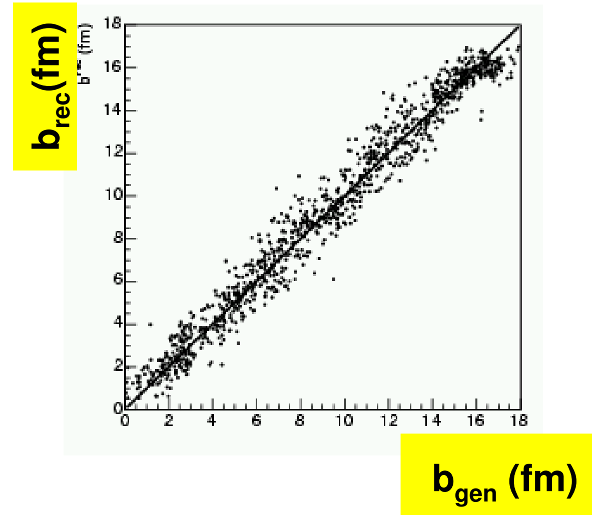
The ZEM has a signal with relatively low resolution, but whose amplitude increases monotonically with centrality.

The correlation between signals measured by ZDC and ZEM allows to determine centrality and define some centrality bins.

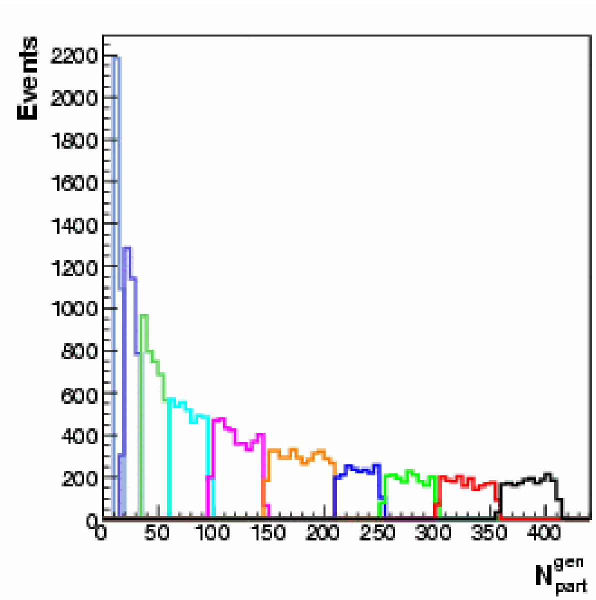
Centrality classes in N_{part}

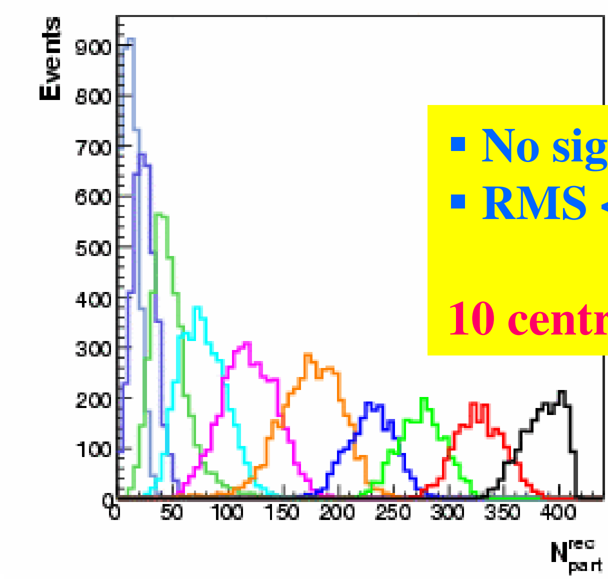
Event by event determination of the centrality

$(E_{ZDC}, E_{ZEM}) \longrightarrow N_{spec} \longrightarrow N_{part} \longrightarrow b$



- **Typical resolutions:**
  - **σ_{Npart}/N_{part} ~ 5 %** **for very central collisions**
  - **σ_{Npart}/N_{part} ~ 25 %** **for semi-peripheral collisions (b ~ 8fm)**





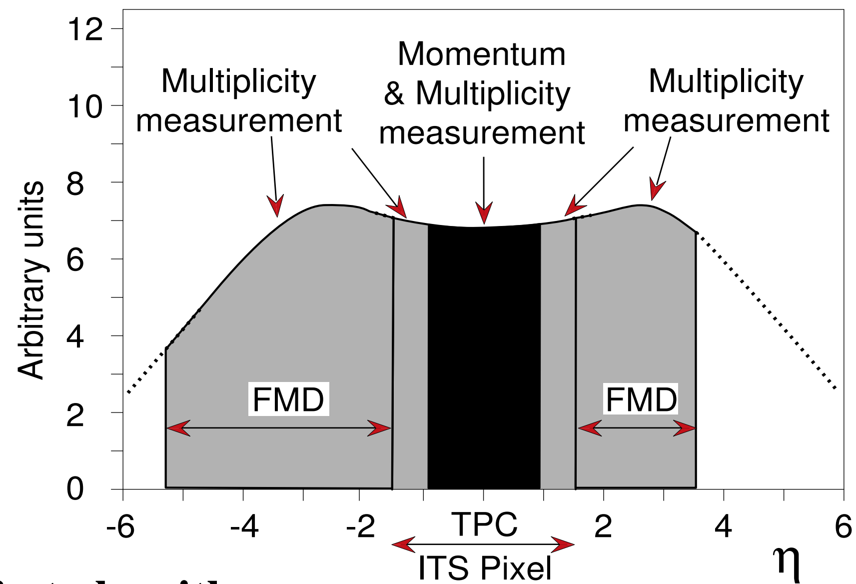
- **No significant bias in the reconstr.**
- **RMS < separation between classes**

10 centrality bins can be safely defined

Multiplicity measurements in ALICE

- **Two detectors:**
  - **SPD (Silicon Pixel Detector, 2 cylindrical layers) in the central region;**
  - **FMD (Forward Multiplicity Detector, 5 rings of silicon strips) at forward rapidities.**

The charged particle multiplicity is measured over 8.8 rapidity units, whereas the momentum is measured in the TPC (and in the Inner Tracking System) over 1.8 rapidity units with optimal resolution.



SPD

We have chosen two relatively simple and fast algorithms:

1) **<u>cluster counting</u> on each pixel layer (|η|<2 first layer, |η|<1.4 second layer);**
2) **<u>counting of tracklets</u> (association of clusters on the two layers, aligned with the estimated vertex position) (|η|<1.4)**

FMD (-3.4<η<-1.7 and 1.7<η<5.1)

Reconstruction of multiplicity based on empty pad counting.

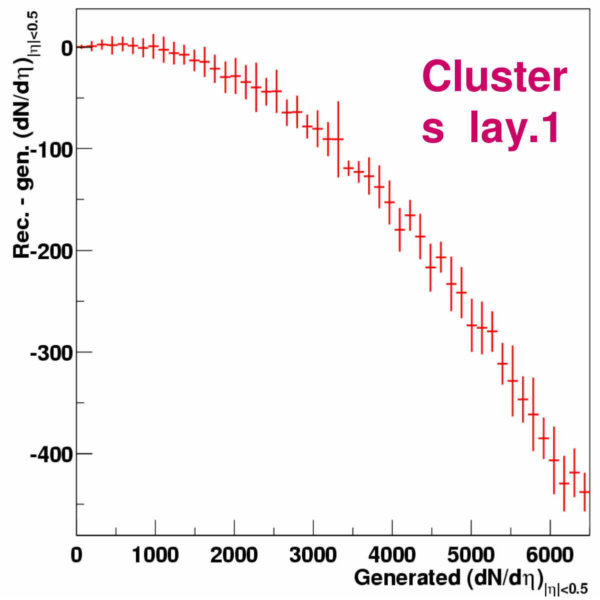
R. Caliandro, R.Fini and T.Virgili, Measurement of multiplicity and dN/dη using the ALICE Silicon Pixel Detector, ALICE Internal Note ALICE-INT-2002-043

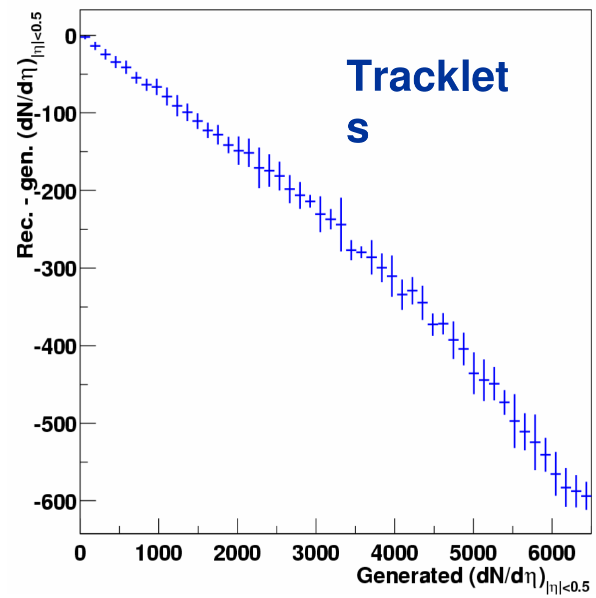
Multiplicity reconstruction in PbPb with the SPD

Accuracy on the reconstructed Multiplicity:

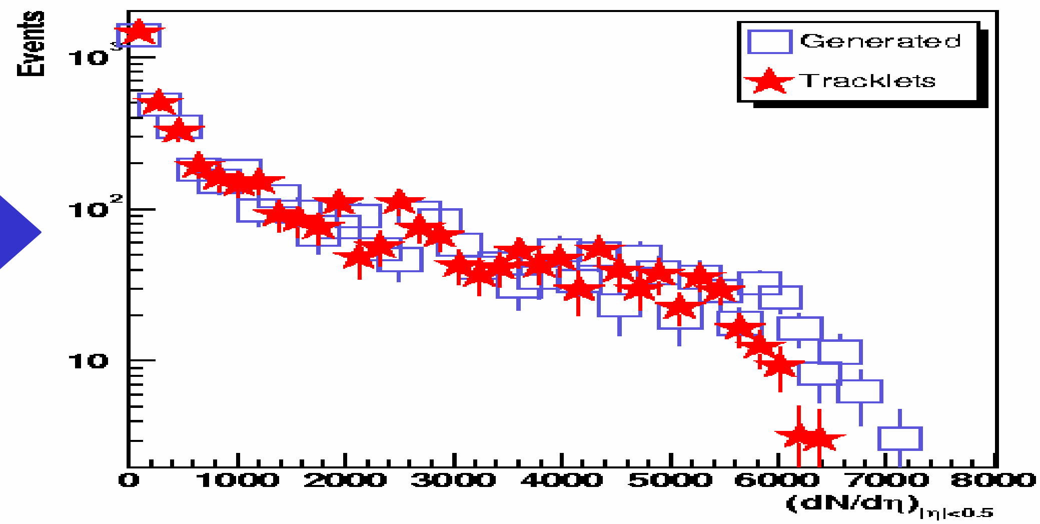
Clusters on layer 1 and tracklets <u>BOTH slightly underestimate multiplicity</u>

Difference <10%

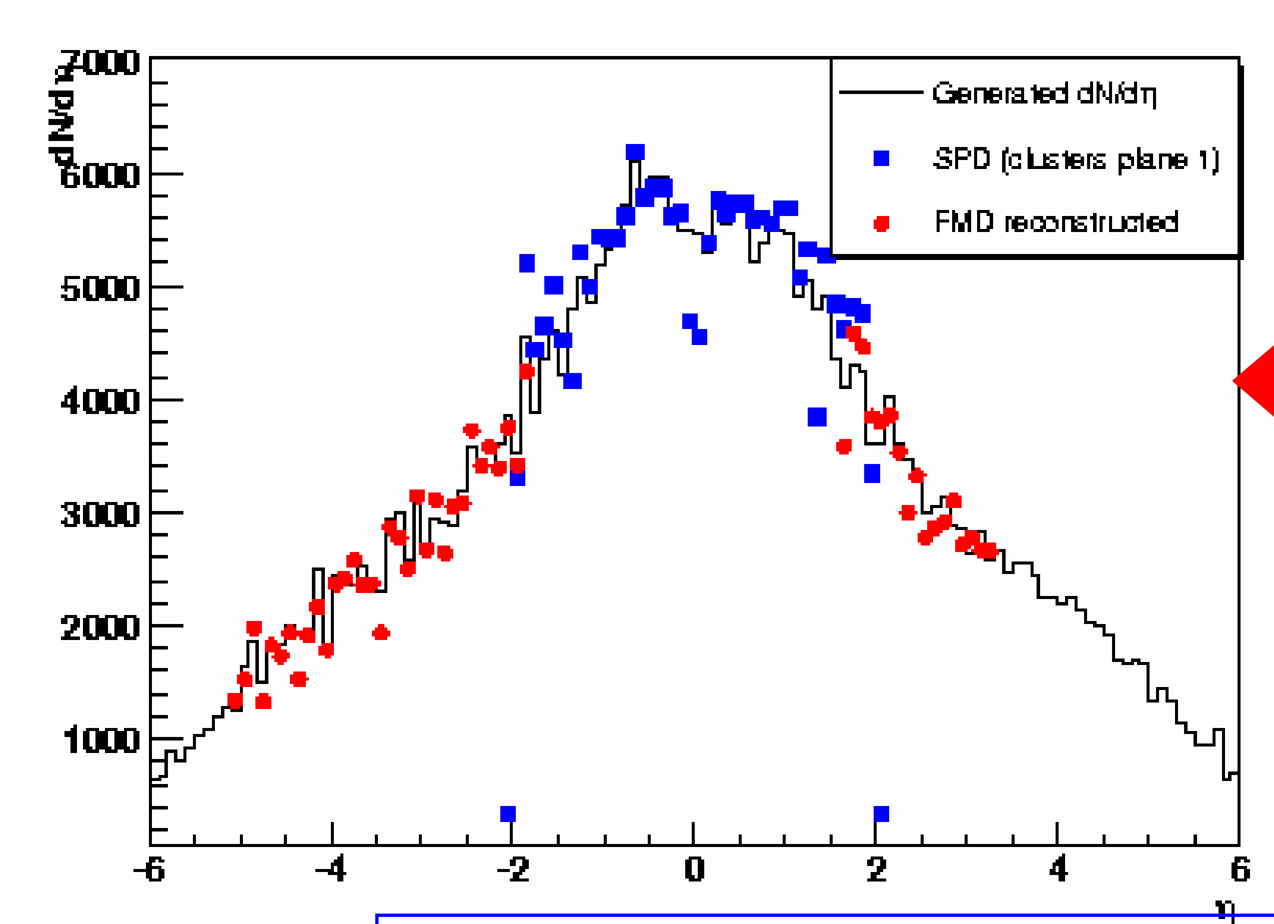




Reconstructed multiplicity distribution with tracklets (HIJING events)



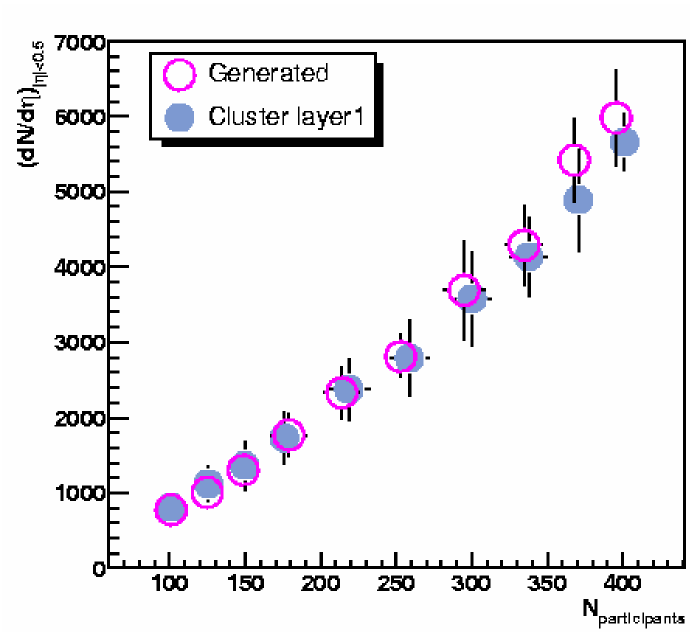
Reconstruction of dN/dη distribution in Pb-Pb with FMD+SPD

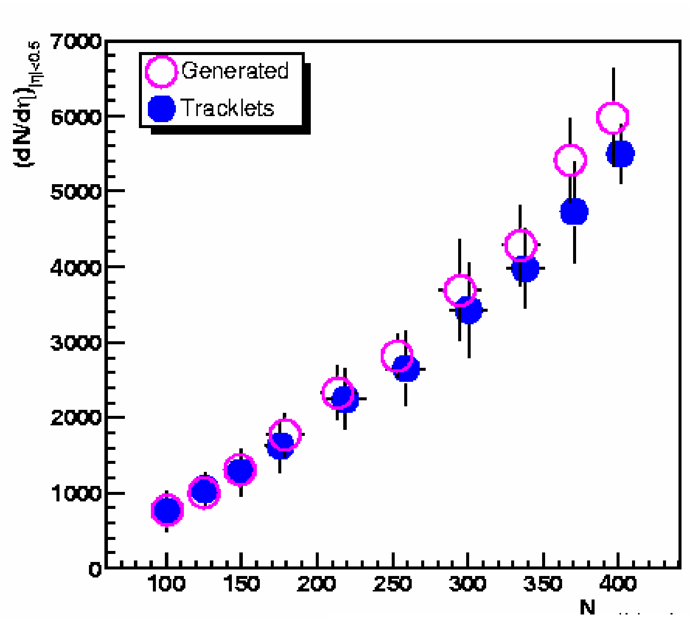


1
Central Pb-Pb
HIJING event

- **We can have in ALICE a coverage up to ~ 10 η-units**
- **Accuracy ~ 7% in 0.1 η bins**

Study of multiplicity versus centrality (à la PHOBOS)





Multiplicity measured with SPD

10 centrality bins in N_{part} estimated event by event from the measured E_{ZDC}

Fit with KN model

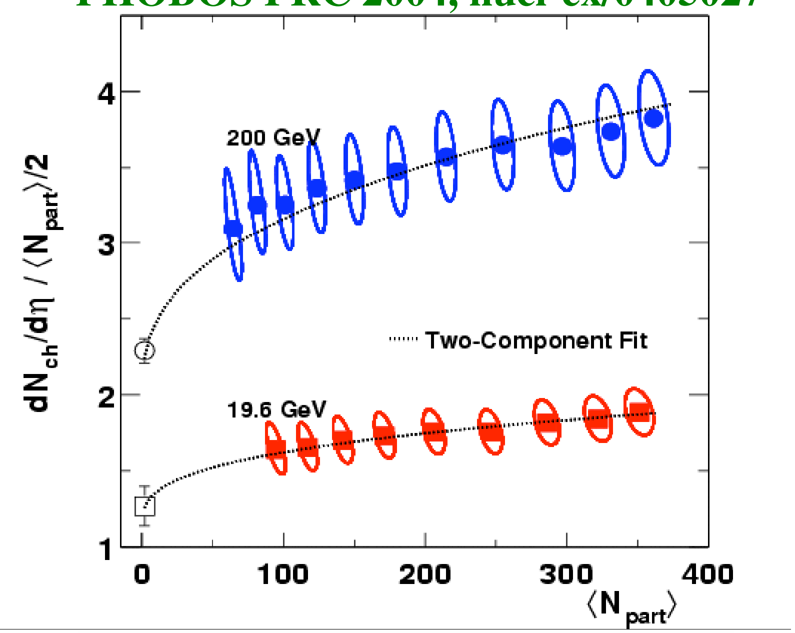
Kharzeev-Nardi model [Phys. Lett. B 507 (2001) 79]

$$\frac{dN_{ch}}{d\eta} = (1-x)n_{pp}\frac{N_{part}}{2} + x n_{pp} N_{coll}$$

$$n_{pp} = 2.5 - 0.25 \cdot \ln(s) + 0.023 \cdot \ln^2(s)$$

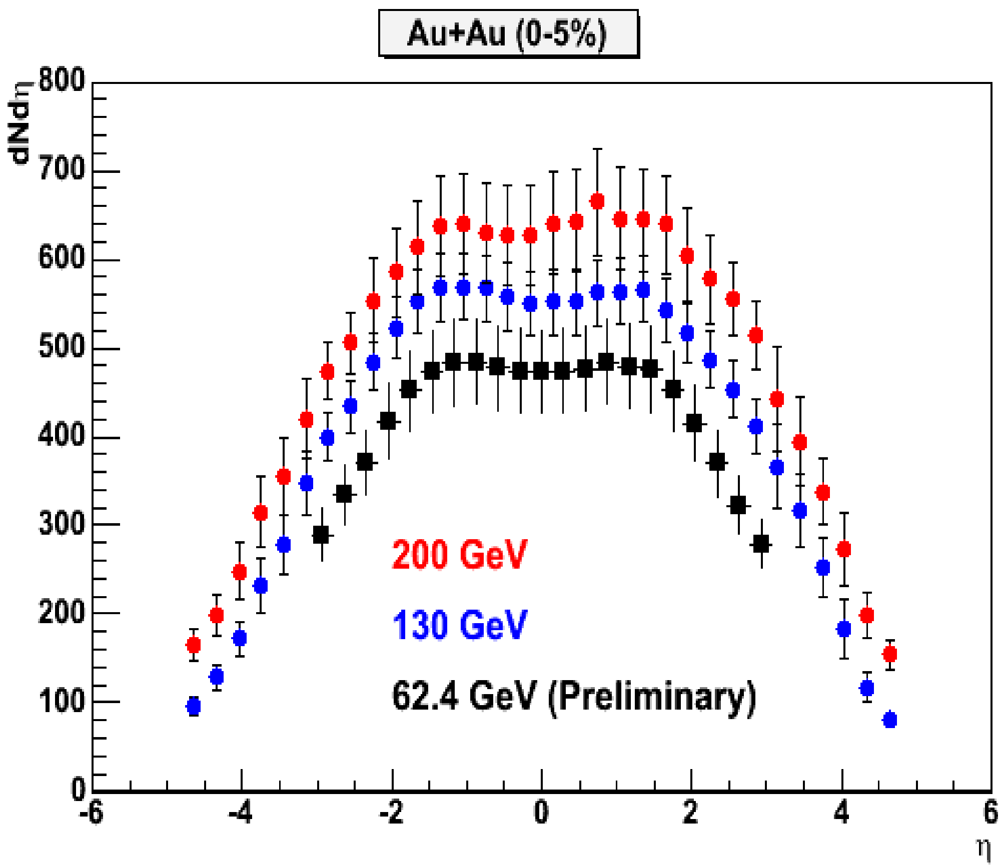
	x
Generated	0.61 ±0.03
Rec. clusters	0.60 ± 0.03
Rec. tracklets	0.57 ± 0.03

PHOBOS PRC 2004, nucl-ex/0405027



$dN_{ch}/d\eta$ and energy density at RHIC

Measurements of charged particle density at midrapidity can be used to estimate the energy density created in a heavy ion collisions using the **Bjorken formula**: $\varepsilon_{BJ} = 3/2 \times(\langle E_t\rangle / \pi R^2 \tau_0)\, dN_{ch}/d\eta$



P. Staszel (BRAHMS), QM2005

When assuming a formation time τ_0=1fm/c the conditions reached at RHIC are:

> 5.0 GeV/fm^3 for AuAu @ 200 GeV

> 4.4 GeV/fm^3 for AuAu @ 130 GeV

> 3.7 GeV/fm^3 for AuAu @ 62.4 GeV

Whereas the energy density reached at the CERN SPS was:

2.7 GeV/fm^3 for PbPb @ 17.2 GeV

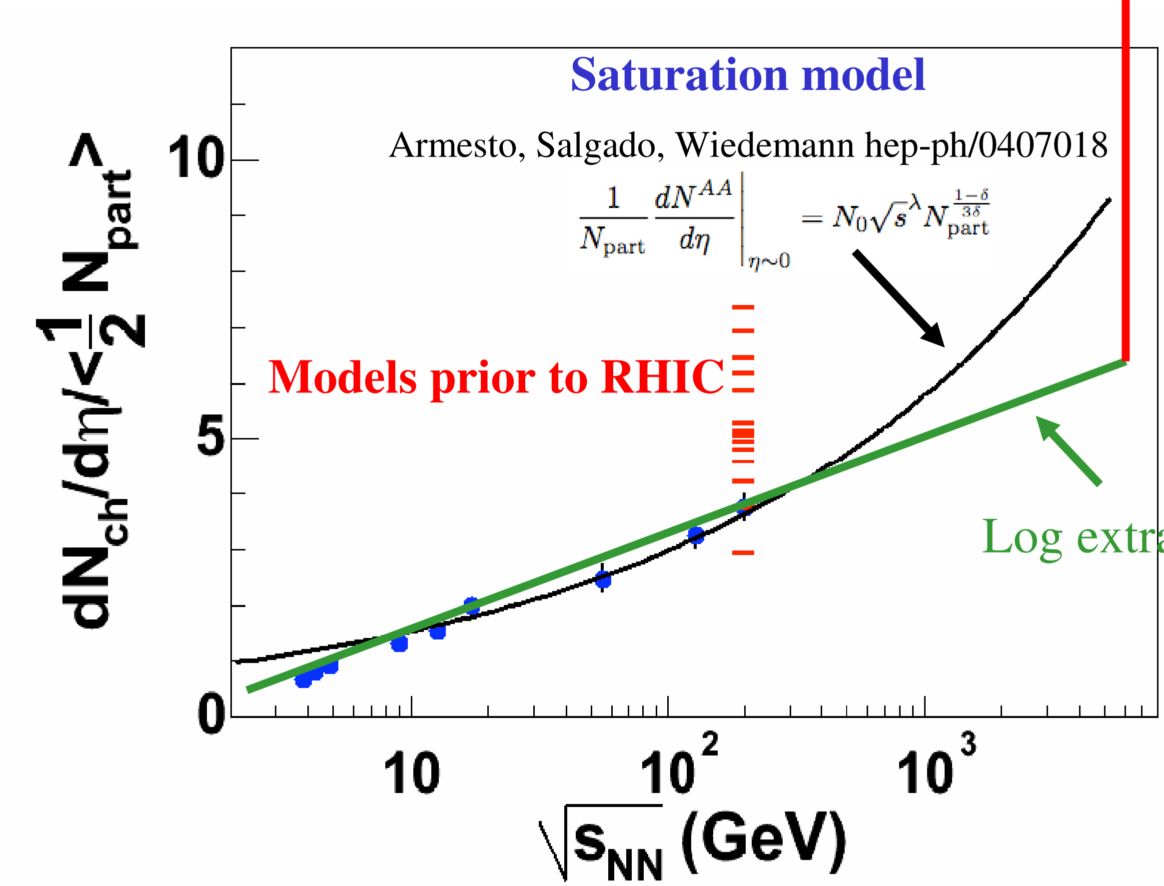
To be compared with the energy density predicted by Lattice QCD

$$\varepsilon_C = 0.6 \text{ GeV/fm}^3$$

for the QGP formation.

Energy dependence of multiplicity: extrapolation to LHC

ALICE Detectors are planned to deal with: dN/dη > 5000



dN/dη ~ 1800

dN/dη ~ 1100

Highlights on physics topics

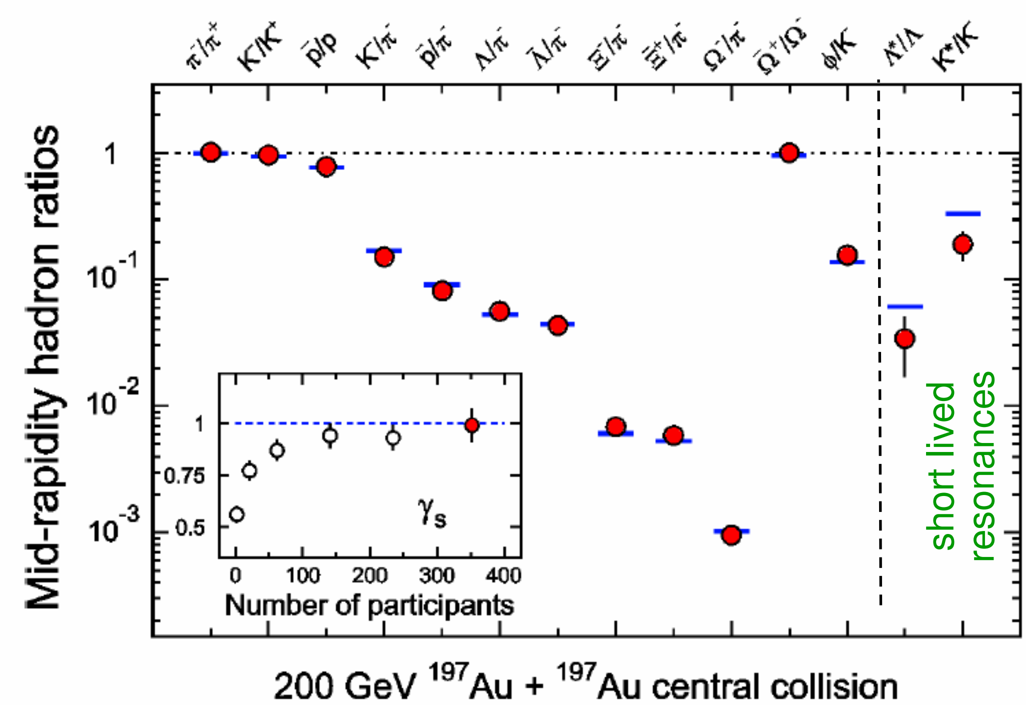
Soft Physics I

- Particle abundances
- Particle spectra and their ratios

Particle yields and chemical freezout at RHIC

- **Particle yields** are established at the **chemical freezout**, and provide information on this relatively early stage (before hadronic expansion, cooling and "thermal freeze-out")

- **Statistical thermal models** (employing hadronic degrees of freedom in a grand-canonical ensemble) are able to reproduce the particle ratios using only **two parameters**: T (chemical freezout temperature)
  μ_B (baryo-chemical potential)



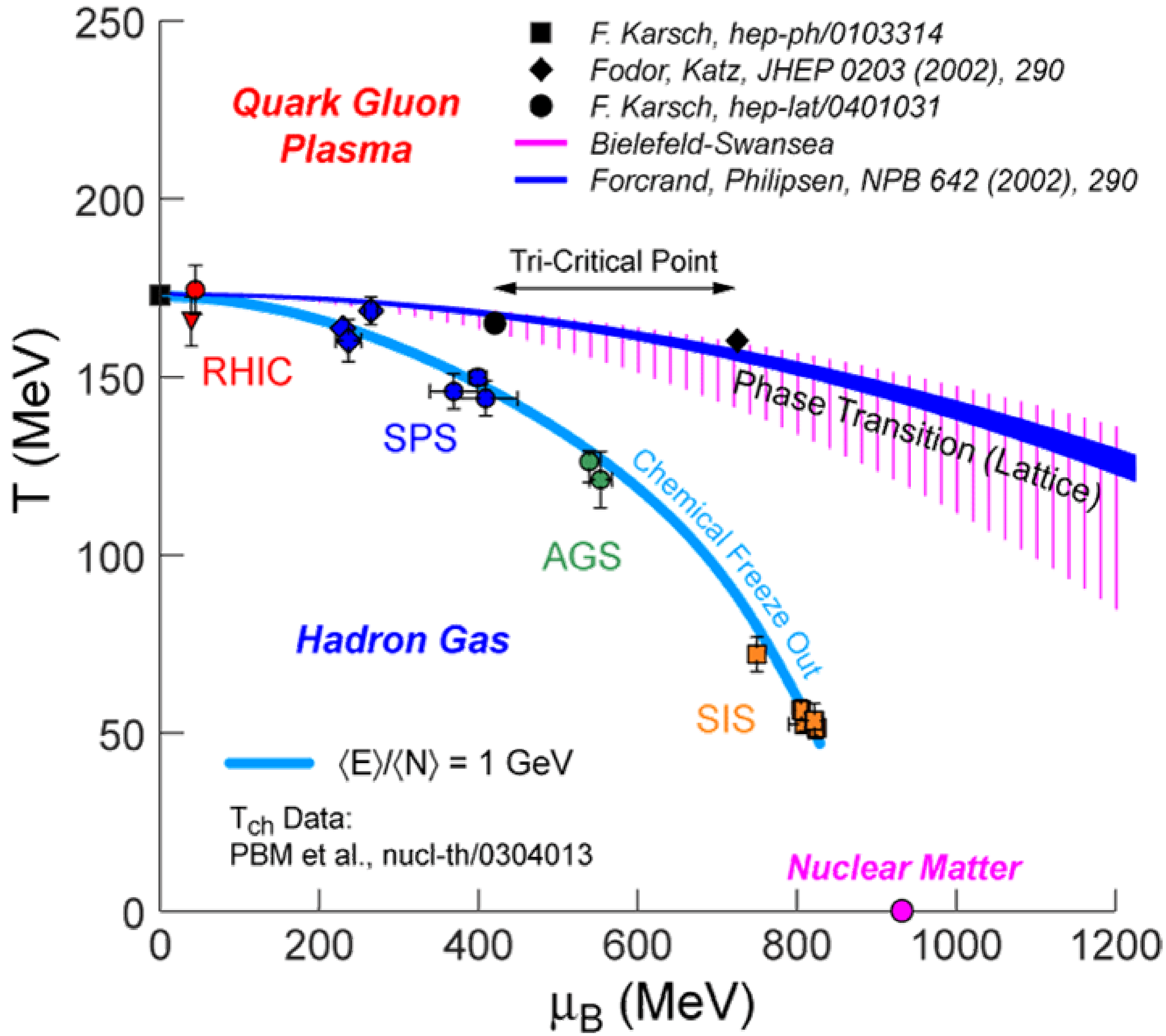
STAR white paper
Nucl Phys A757 (05) 102

From the fit of the STAR data:

$T_{ch} \approx 165 \pm 10$ MeV ~ T_{crit} (LGT)
$\mu_B \approx 25$ MeV

The ability of the stat.model to fit the particle yields leads us to conclude that the experimental data at RHIC (and SPS) show a high degree of chemical equilibration

QCD phase diagram



At RHIC:

T = 177 MeV

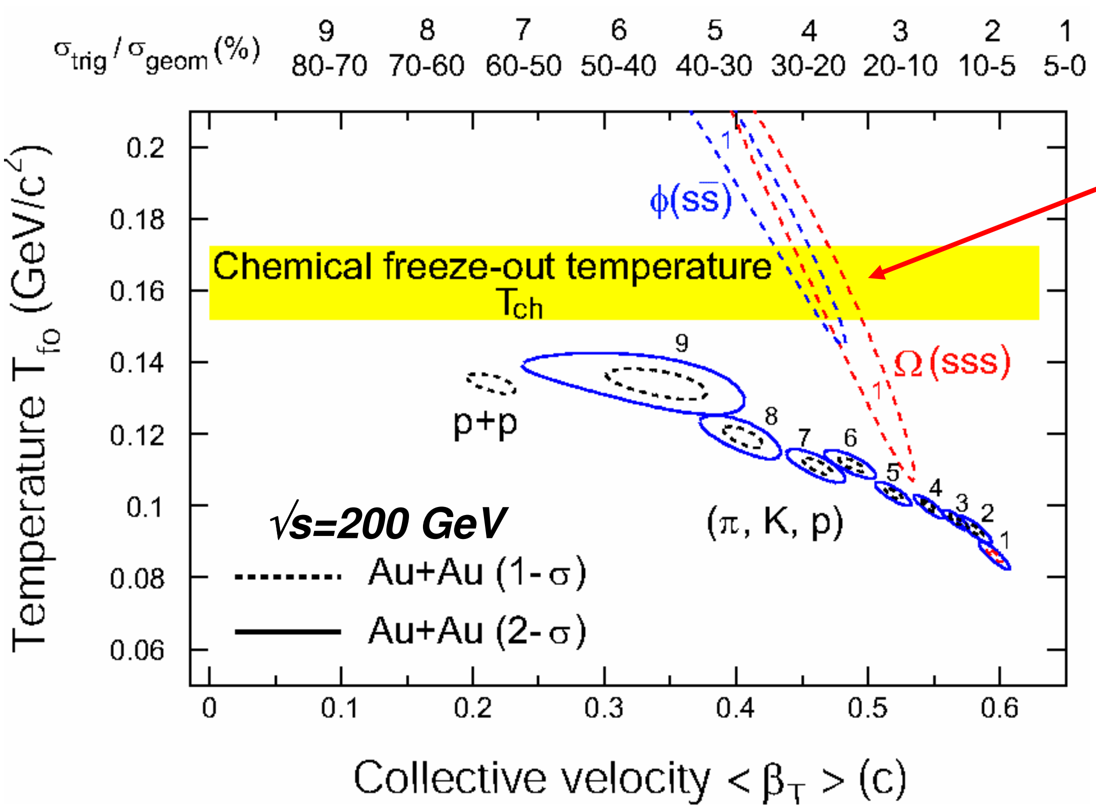
T ~ $T_{critical}$ (QCD)

Unified statistical picture from SIS to RHIC.
What about LHC ?

Kinetic freezout at RHIC

Thermal fit (using an inverse slope parameter 1/T) of the particle spectra provides information on the dynamics of the expansion and the T of the system at the **kinetic decoupling** (thermal freezout), when particle cease interacting.

Models based on hydrodynamics can be used to estimate **T_{fo} (freezout)** and the mean transverse **(radial) flow velocity $\langle\beta_T\rangle$** simultaneously, and to study their behaviour as a function of centrality and particle type.



Multi-strange hadrons (in the 5% most central collisions) :

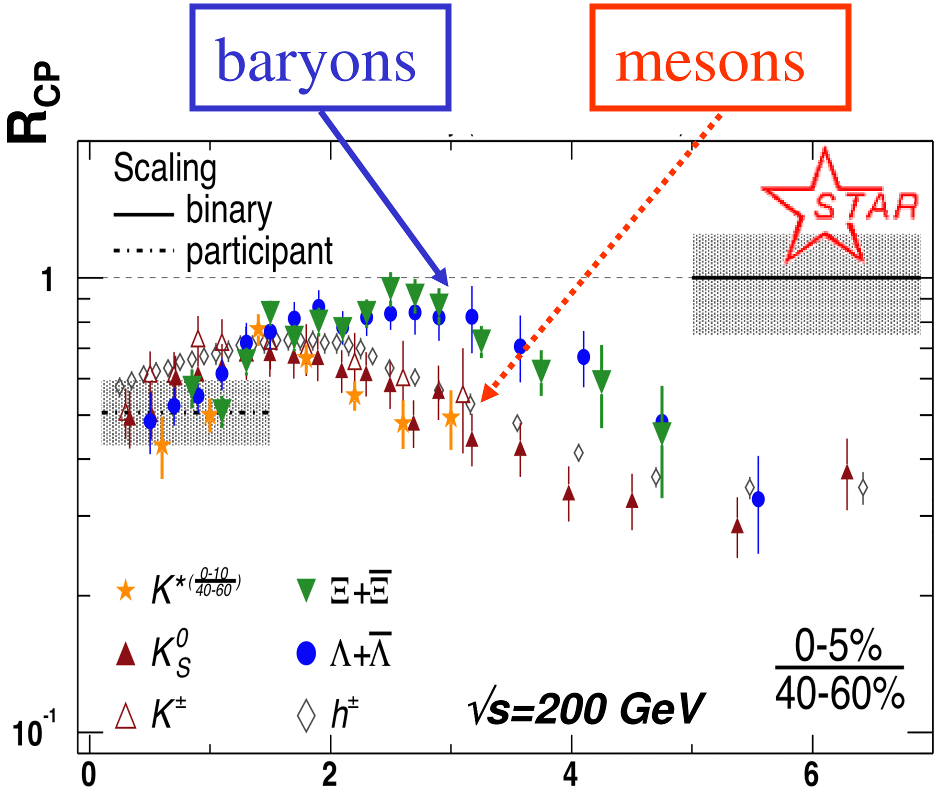
- no overlapping χ^2 contour with (π, K, p) at the same centrality
- $T_{kin\ freezout} \sim T_{chemical\ freezout}$ (from statist. model analysis)
- **(π, K, p)** acquire **stronger collective flow during the cooling phase** between T_{kin} and T_{ch}

STAR: Nucl. Phys. Rev. A757 (2005) 102

Ratios of hadron spectra: R_{CP}

$$R_{CP}(p_T) = \frac{< N_{coll}^{peripheral} >}{< N_{coll}^{central} >} \frac{d^2 N^{central} / dp_T d\eta}{d^2 N^{peripheral} / dp_T d\eta}$$

Binary scaled ratio of hadron yields in a central over a peripheral bin (the spectra are normalized to N_{coll}, the number of binary collisions in each centrality bin)



Different suppression pattern for mesons and baryons at intermediate p_T

For baryons the suppression is smaller. This supports the constituent **quark coalescence (recombination) model**

STAR: Nucl. Phys. Rev. A757 (2005) 102

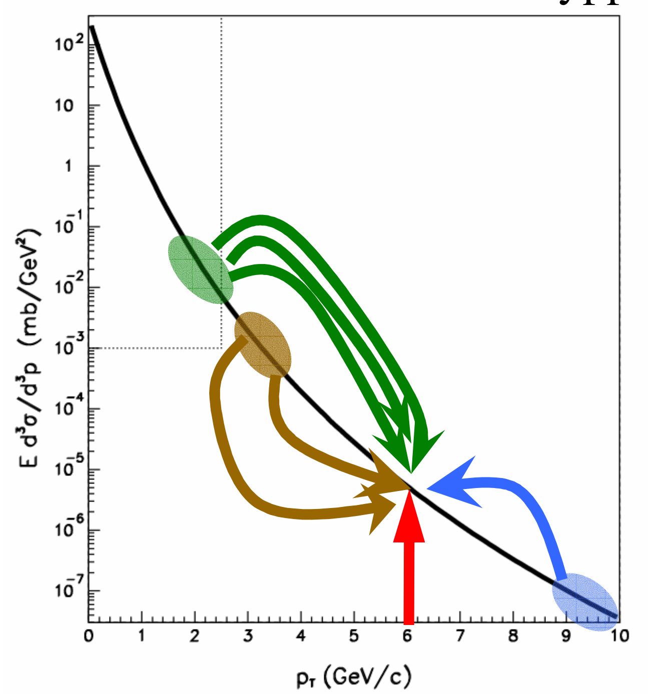
Coalescence: possible mechanism at intermediate p_T

- The *in vacuo* **fragmentation** of a high momentum quark to produce hadrons *competes* with the **in medium recombination** of lower momentum quarks to produce hadrons

- Example: creation of a 6 GeV/c π or p
  - Fragmentation: $D_{q \rightarrow h}(z)$
    - produces a 6 GeV/c π from a 10 GeV/c quark
  - Recombination:
    - produces a 6 GeV/c π from *two* 3 GeV/c quarks
    - produces a 6 GeV/c proton from *three* 2 GeV/c quarks

Recombination yields **more baryons** at a given p_T since the three combining quarks have a larger yield at $p_T/3$ compared to the two q at $p_T/2$

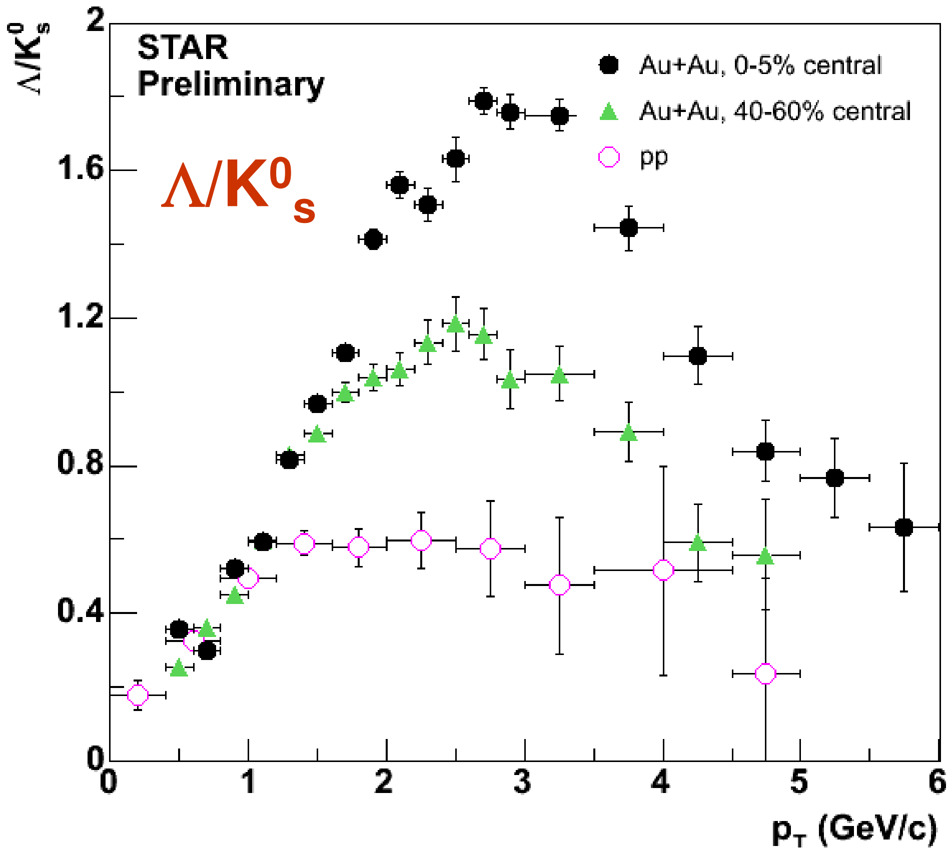
B.Hyppolite



...requires the assumption of a thermalized parton phase... (which) may be appropriately called a quark-gluon plasma

Fries, et al, PRC 68, 044902 (2003)

Baryon excess at intermediate p_T



Intermediate p_T range:

1) Low p_T limit can be define by the validity range of Hydro.

2) At high p_T limit, the baryon and meson should merge again.

At RHIC, a high p_T limit at 6 GeV/c is found.

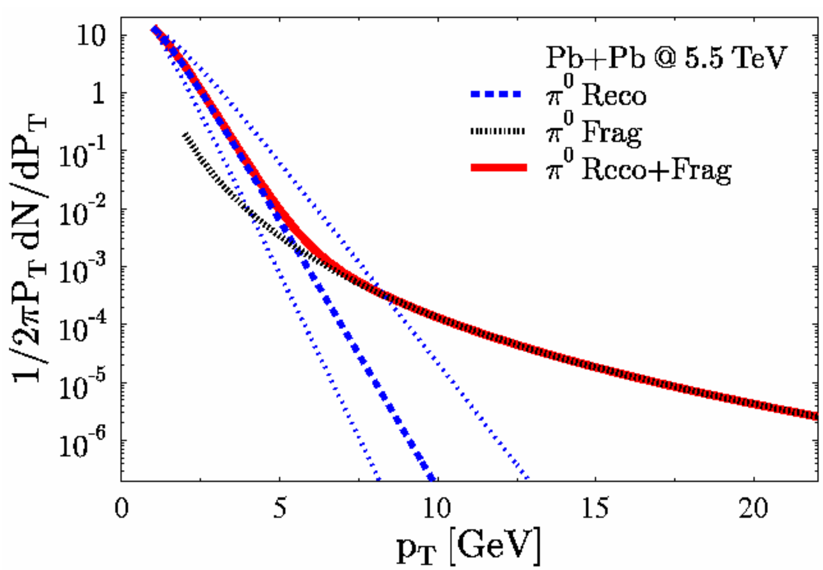
In order to describe the magnitude of the baryon/meson ratio and the location of the maximum the contribution of both coalescence and the **mass-dependent radial flow is needed**. So the fragmentation dominance for baryons starts at higher p_T
This effect increases with centrality .

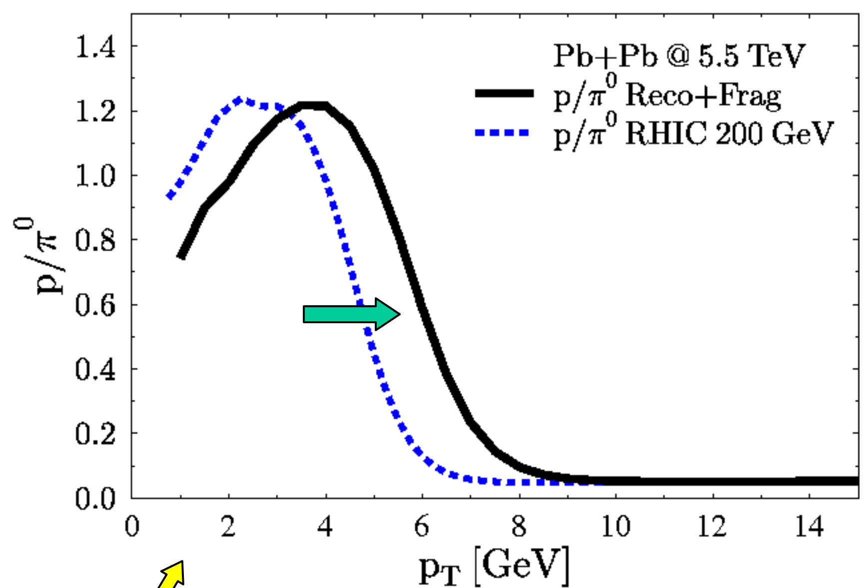
What to expect at LHC energies

Calculation in the scenario recombination + pQCD fragmentation must imply an assumption on transverse radial flow extrapolation

Fries and Müller, EJP C34, S279 (2004)

$T_{freezout}$ =175 MeV, $\beta_T = 0.75$





Amplitude of the ratio at the LHC is the same as at RHIC but the limit of the intermediate p_T region is pushed to higher p_T

But still within the ALICE p_T reach !!

Ratios of hadron spectra: R_{AA}

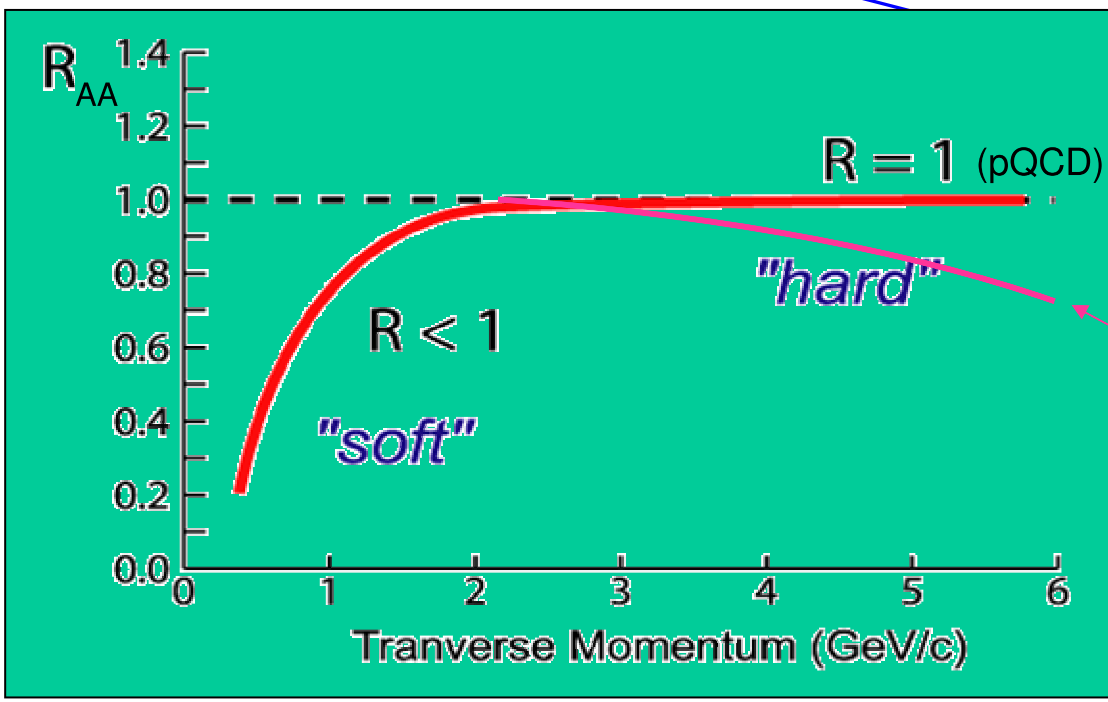
Nuclear Modification Factor R_{AA}:
AA = Nucleus-Nucleus
NN = Nucleon-Nucleon

AA cross section

$$R_{AA}(p_T) = \frac{d^2N^{AA}/dp_T d\eta}{T_{AA} d^2N^{NN}/dp_T d\eta}$$

NN cross section

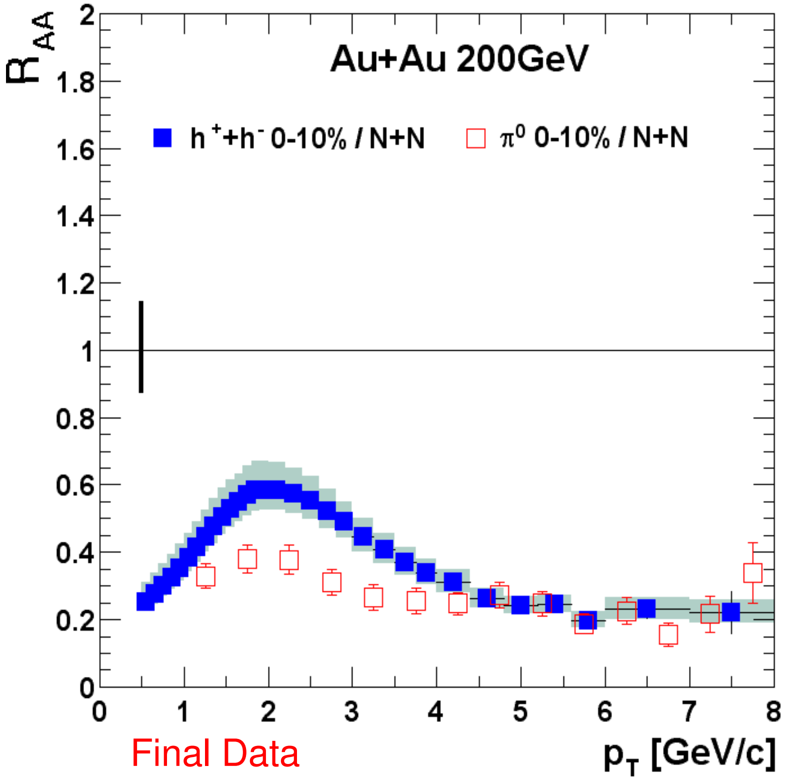
Nuclear overlap integral:
 # binary NN collisions / inelastic NN cross section



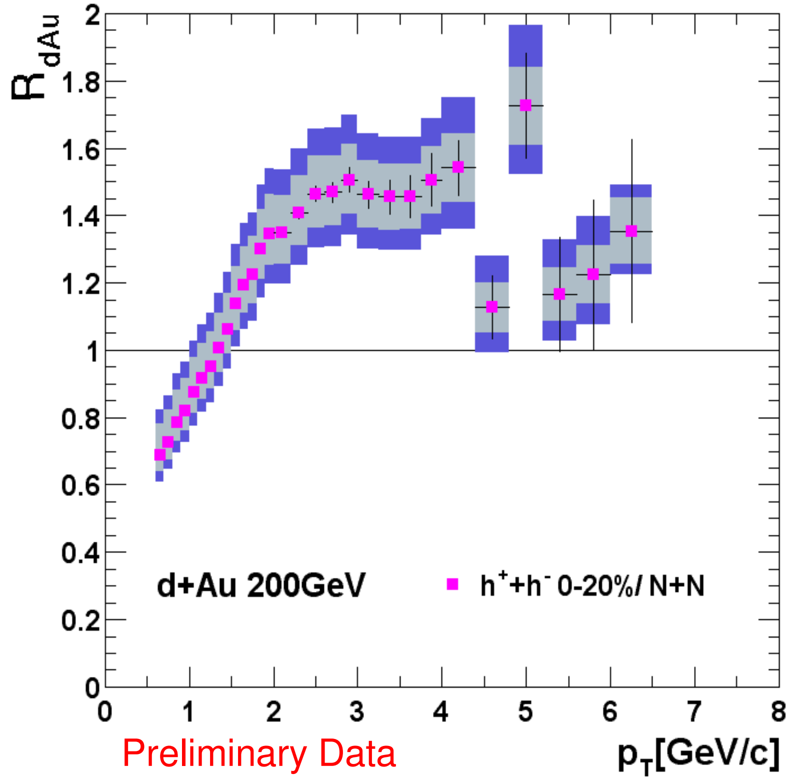
Parton energy loss
→ R < 1 at large P_t

Centrality Dependence of R_{AA}

Au + Au Experiment



d + Au Control Experiment

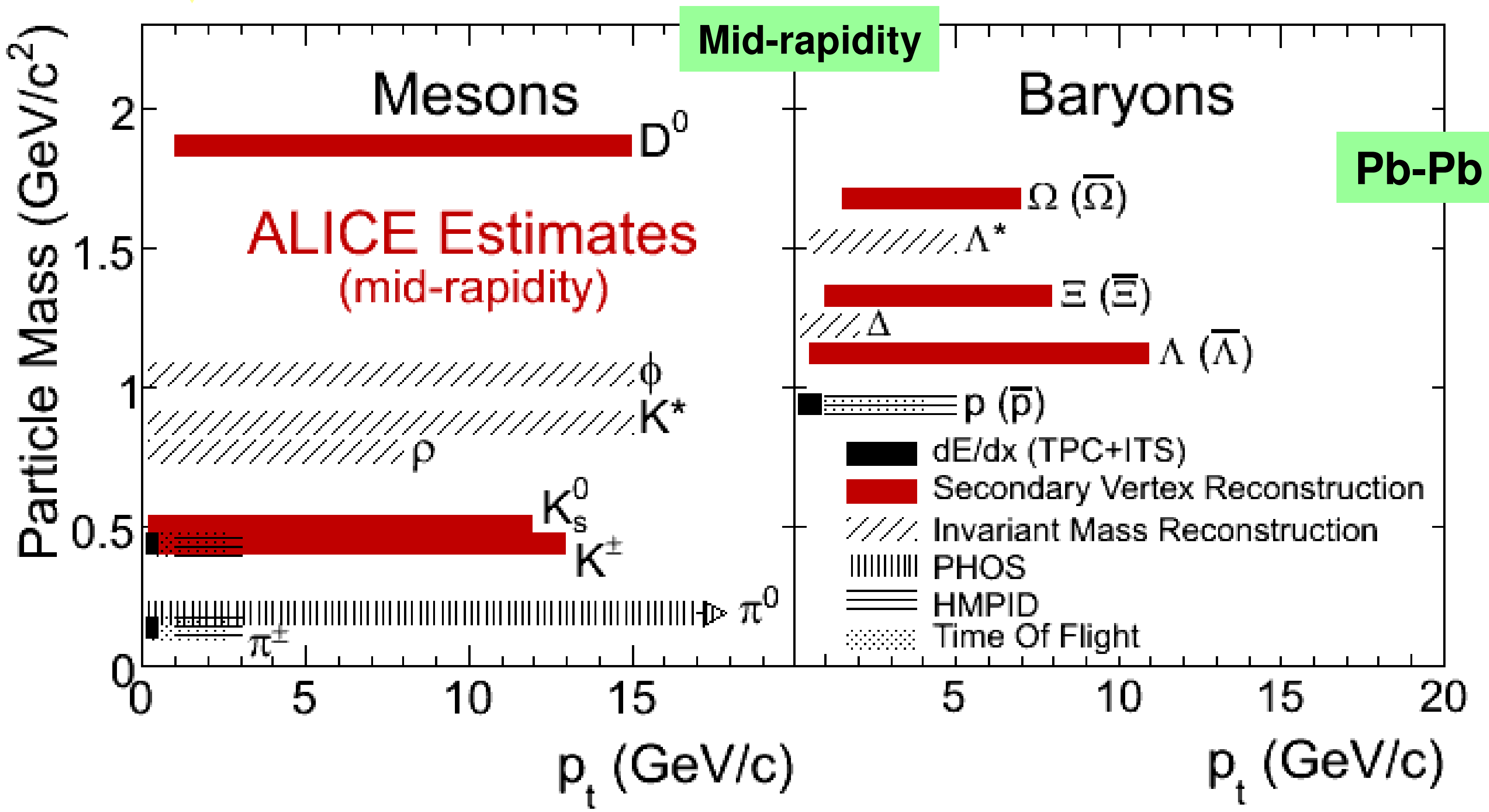


- Dramatically different and opposite centrality evolution of Au+Au experiment from d+Au control.
- High p_T hadron suppression is clearly a final state effect (partonic energy loss in a dense medium) and not an initial state effect (gluon saturation).
- $R_{dAu} > 1$ at intermediate p_T shows a Cronin enhancement (multiple scattering)

Particle identification range with ALICE (in one year)

p_T range (PID or stat. limits) for 1 year: 10^7 central Pb-Pb (or 10^9 min. bias pp)

π, K, p: 0.1- 0.15 → 50 GeV (by using relativ.rise of dE/dx in the TPC)
Weak or strong decaying particles: up to 10-15 GeV



BEGIN OF THE SECOND LECTURE

Contents

- Nucleus-nucleus collisions (and p-p) at the LHC
- The ALICE experiment
- Event characterization
- Highlights on some physics topics *
  - Soft physics I
    - Particle abundances and spectra
  - Soft physics II
    - strange baryons and elliptic flow
  - Heavy Flavours and quarkonia
  - Jets
- Conclusions

Lecture 1

Lecture 2

* Results of studies published on Physics Performance Report Vol.II, CERN/LHCC 2005-030

Highlights on physics topics

Soft Physics II

- Strange baryons
- Elliptic flow

Strangeness enhancement

- An enhancement in the production of rare strange hadrons was among the first signatures proposed for QGP observation in relativistic heavy ion collisions
  - *J.Rafelski and B. Müller, Phys. Rev. Lett 48 (1982) 1066; Phys. Rev. Lett. 56 (1986) 2334.*
- If deconfinement has occurred, the reactions leading to strangeness production are partonic: they have lower thresholds and higher cross sections, especially if the strange quark mass reduces owing to the associated <u>partial restoration of the chiral simmetry</u>.
- Strangeness enhancement of single-strange particle observed in nucleus-nucleus collisions already at rather low energies
- Multi-strange baryon enhancement observed at SPS (and then at RHIC)

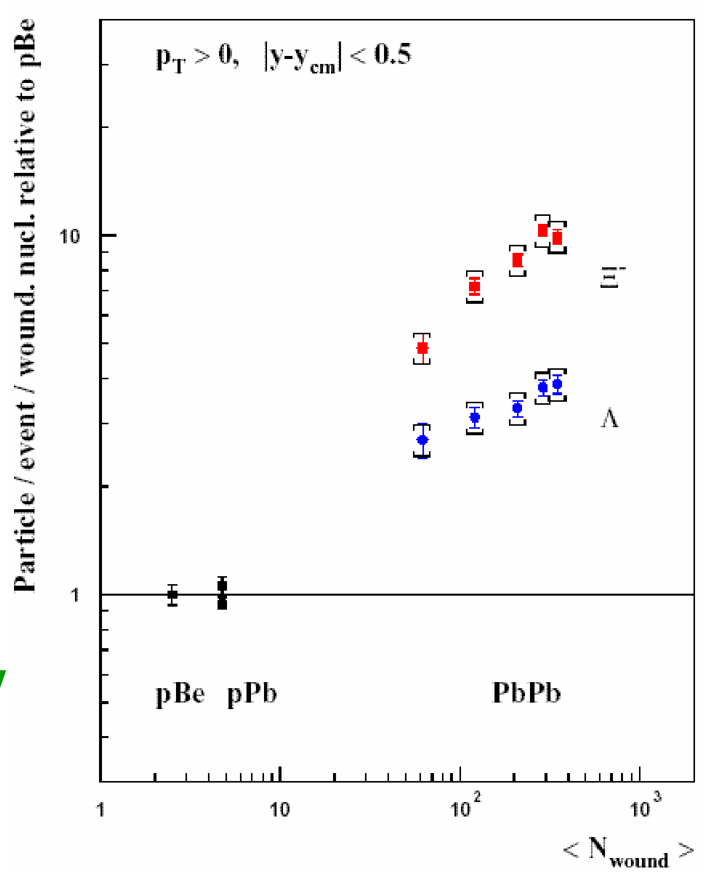
Strangeness enhancement in PbPb at the CERN SPS

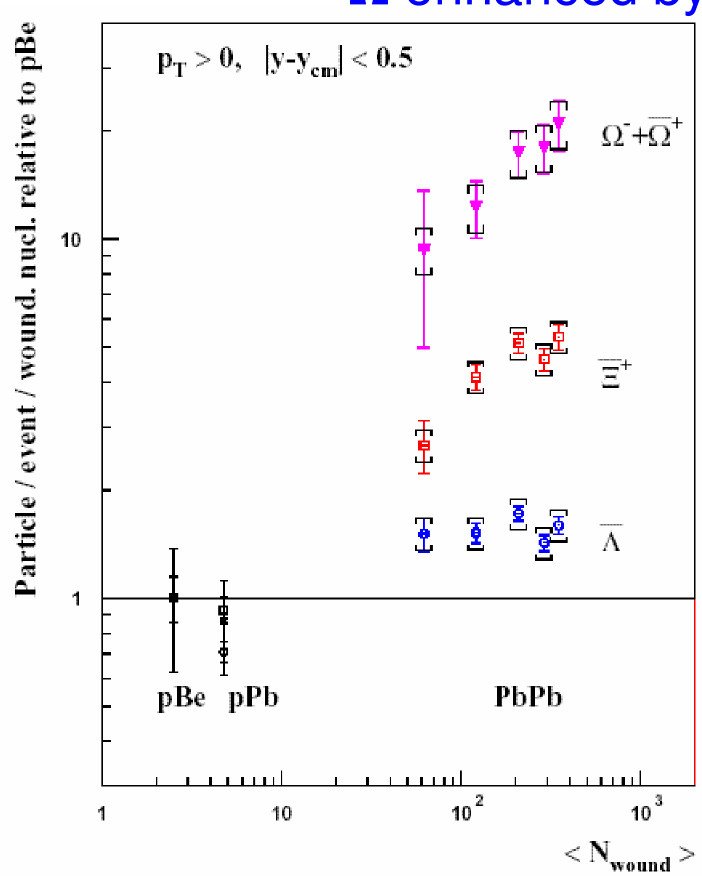
Enhancement = yield per participant nucleon in PbPb relative to pBe

An enhancement, increasing with the centrality of the PbPb collision, has been observed in NA57 for various strange baryons at midrapidity

Ω enhanced by a factor **20**

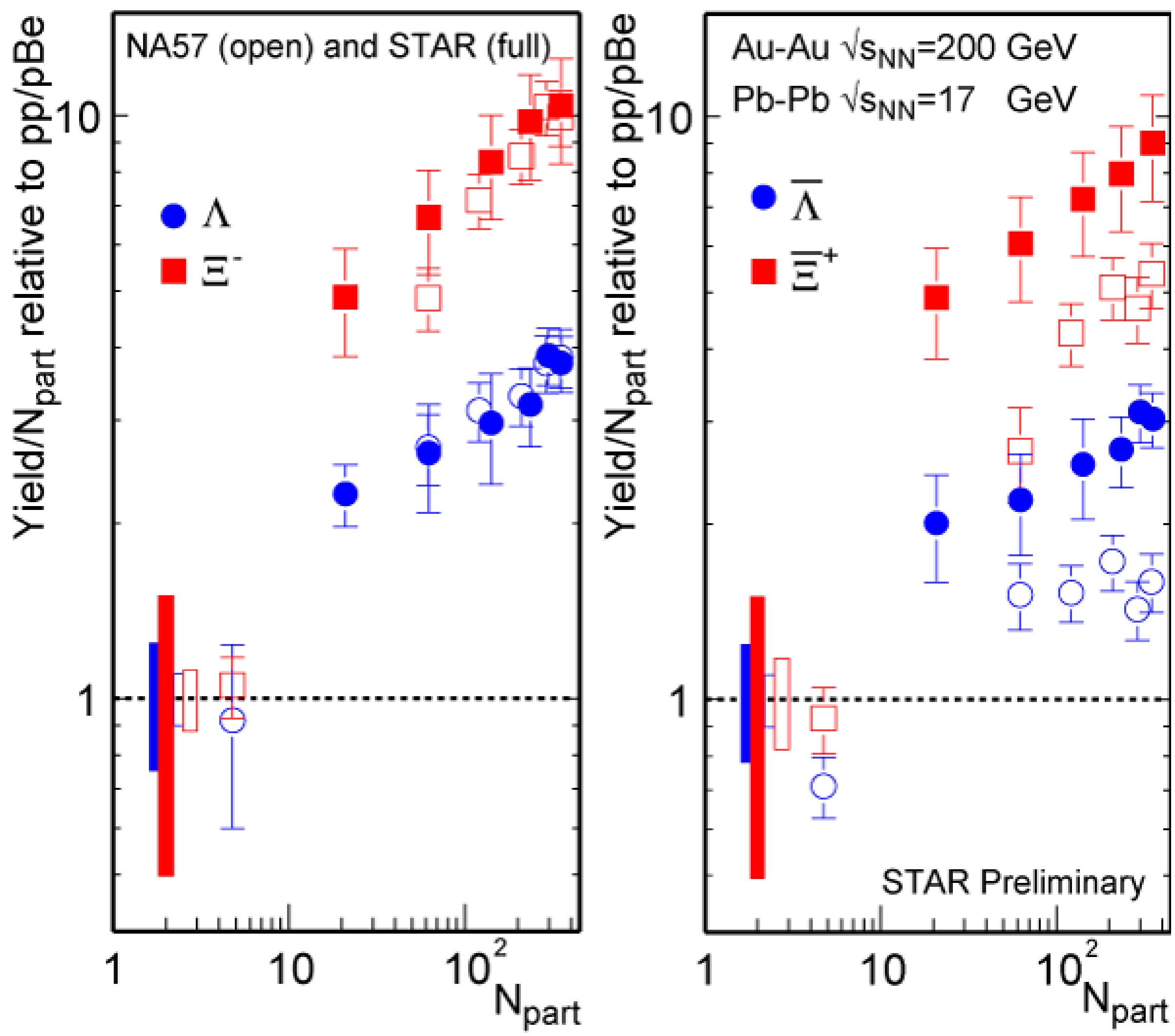
NA57





Strangeness enhancement in AuAu at RHIC

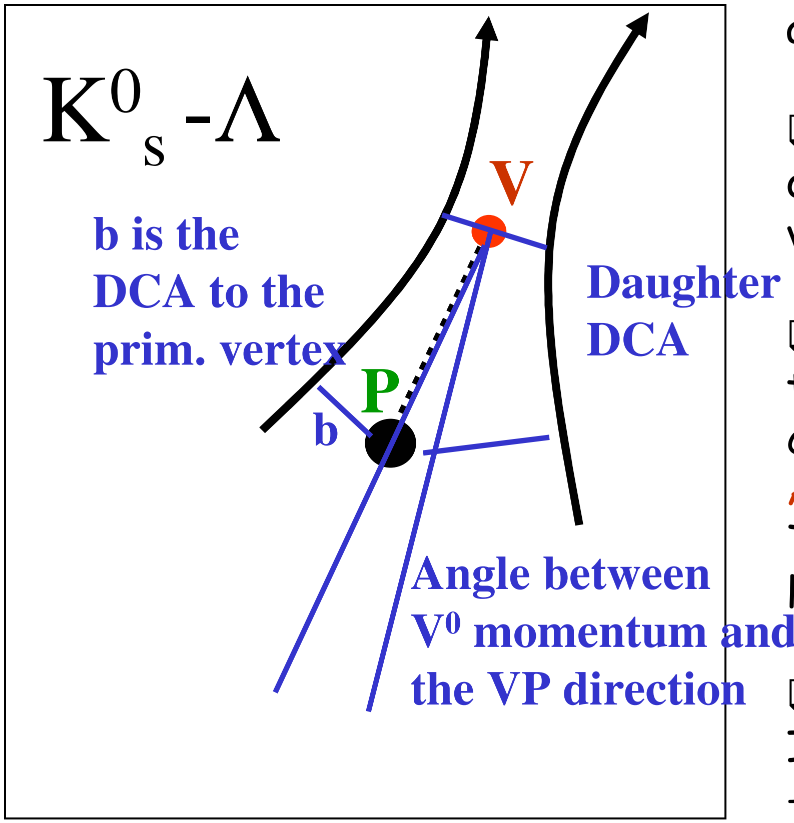
Enhancements are the same or even bigger at RHIC than at SPS



STAR vs NA57 (QM2005)

Secondary vertex reconstruction in ALICE
Hyperon decays with V^0 topologies

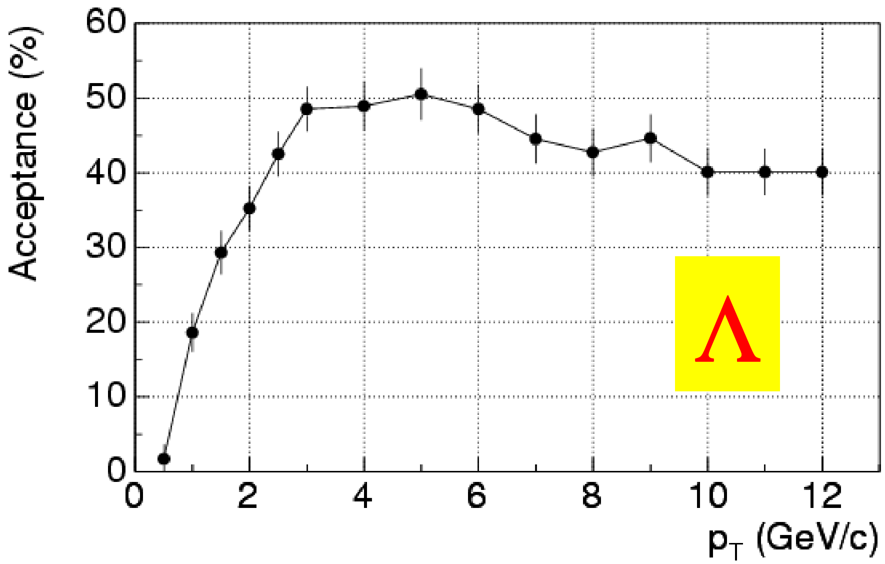
$Ex: \Lambda \to p\pi^- (\text{B.R.} \approx 64\%)$

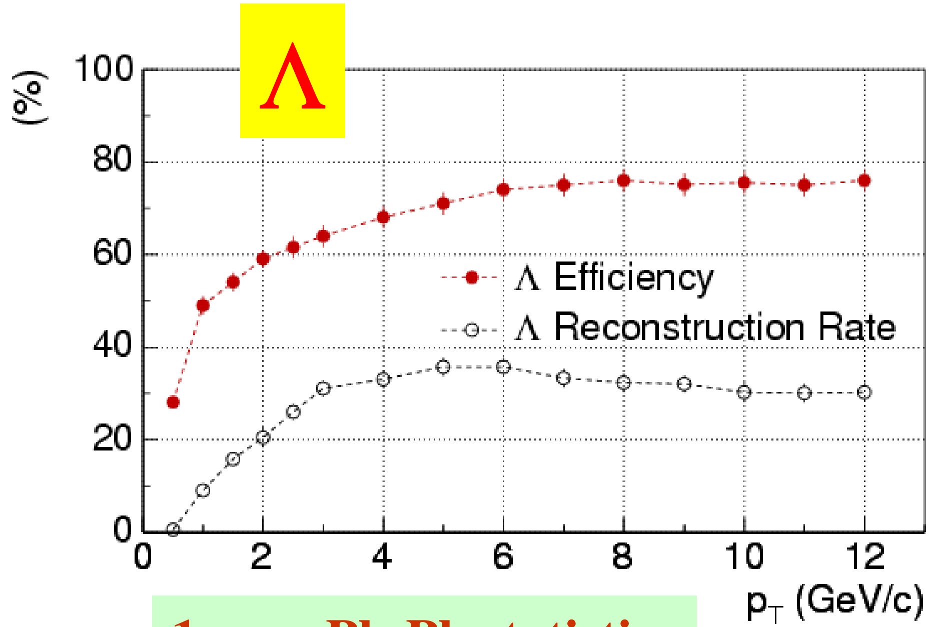


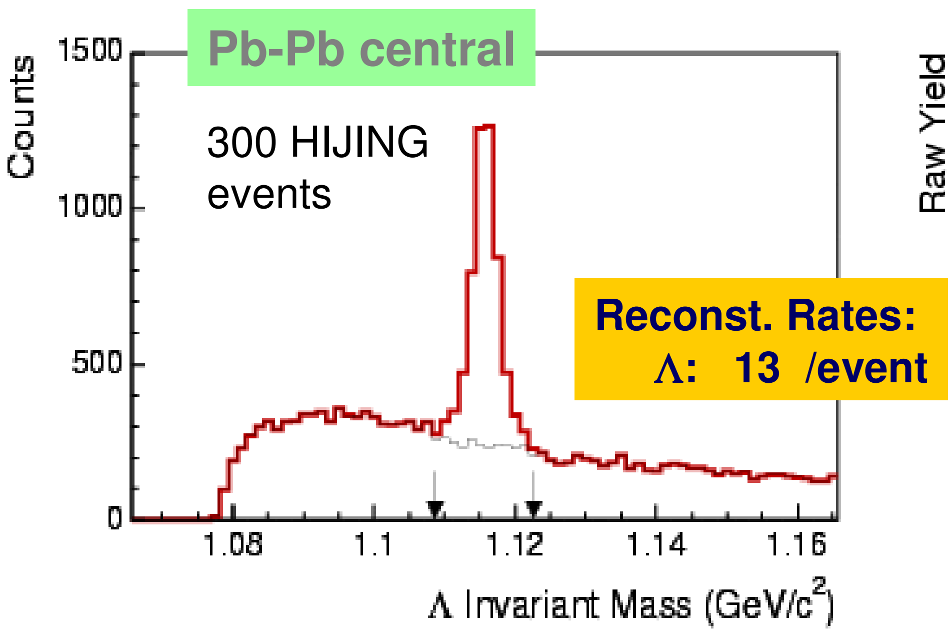
Finding procedure based on a topological identification (L. Gaudichet)

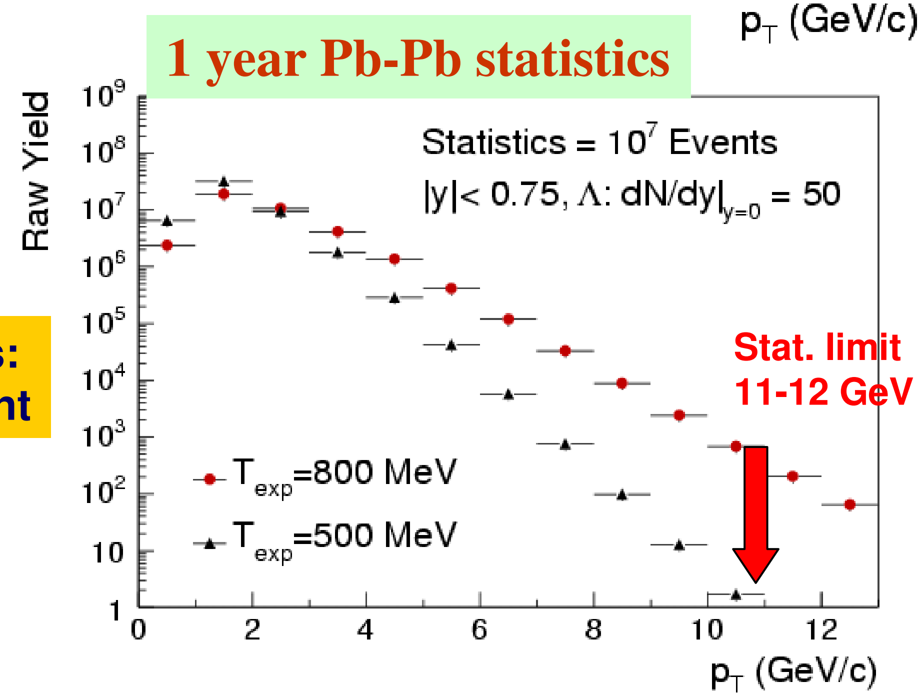
- Reconstruction of the primary vertex P with hits association in the 2 innermost silicon-pixel layers
- Selection of secondary tracks (in TPC) via cuts on impact parameter b with respect to the primary vertex (tracks rejected for b too small)
- Combination of each secondary track with all the others with opposite charge. Numerical calculation of DCA (distance of closest approach). A pair is rejected when DCA is too large.
  The half-point at the minimum DCA is the localization of the vertex V of the V^0 candidate.
- Only vertices V inside a fiducial volume are kept.
  Its maximum size depends on a compromise between
  - need for a low background (small radius)
  - need for high reconstruction rate (bigger radius)
- Checks whether the momentum of the candidate V^0 points well back to the primary vertex P. A cut on the cosine of the angle between V^0 momentum and the VP direction is applied.

Example: Λ reconstruction in ALICE







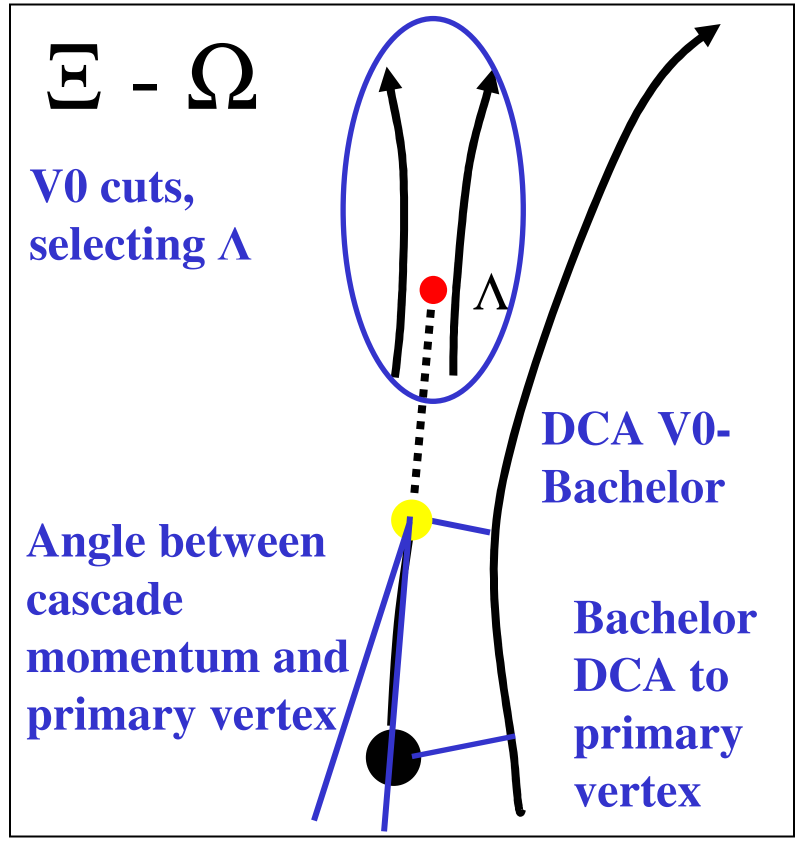


Secondary vertex reconstruction in ALICE
Hyperon decays with cascade topologies

- The search of the V^0 candidate (from the decay of the cascade particle) allows that it has a large impact parameter with respect to the primary vertex

- The V^0 candidates within the mass window have to be combined with all possible "bachelors". The association is accepted if the DCA is small enough.

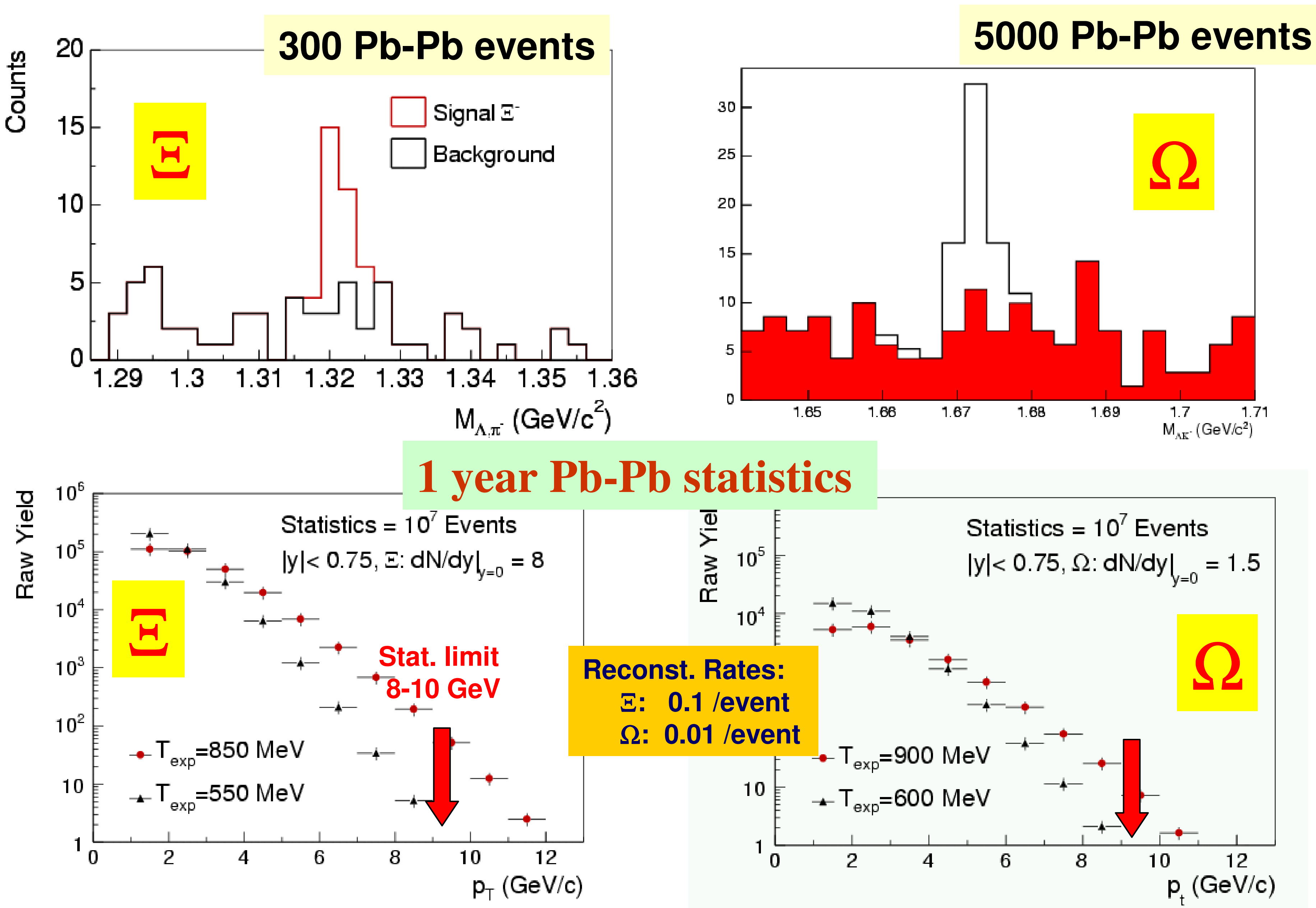
- Checks whether the momentum of the Candidate cascade points well back to the primary vertex P. A cut on the cosine of the angle between cascade momentum and the VP direction is applied.



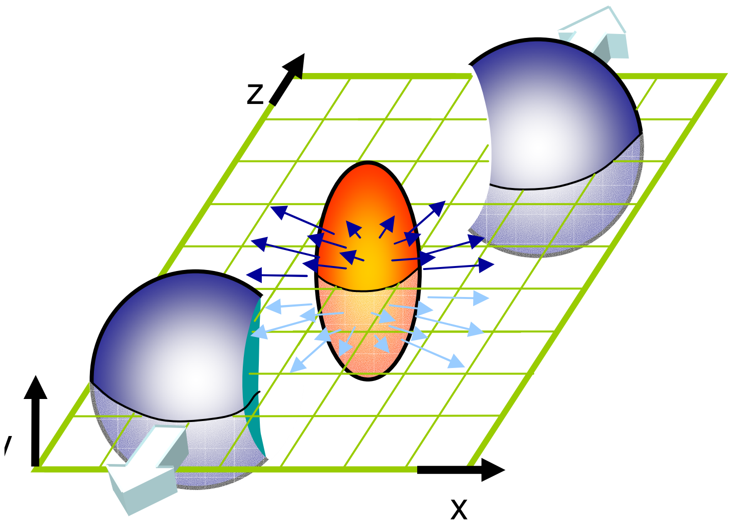
$$Ex : \Xi \rightarrow \Lambda\pi^- (\mathrm{B.R.} \approx 100\%)$$

$$\Lambda \rightarrow p\pi^- (\mathrm{B.R.} \approx 64\%)$$

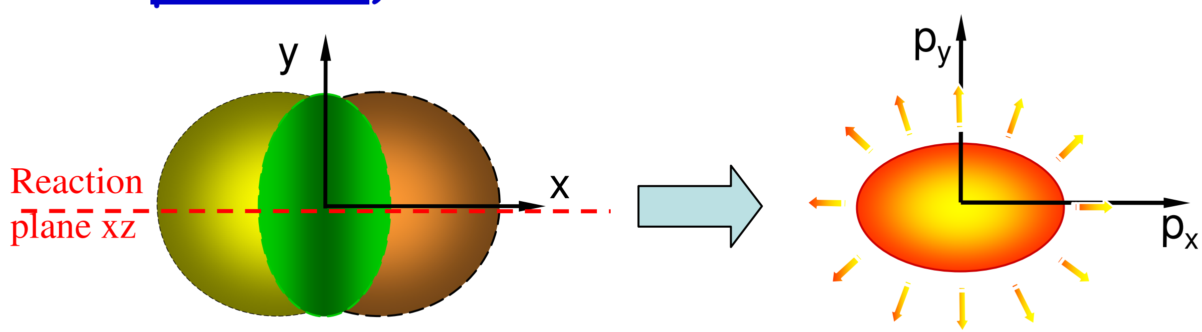
Multi-strange hyperon reconstruction in ALICE

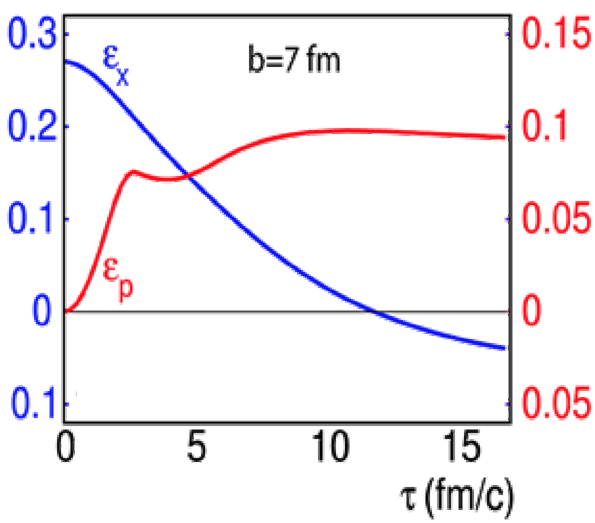


Anisotropic transverse flow



- In non-central nucleus-nucleus collisions, at t=0:
  - geometrical anisotropy (almond shape)
  - momentum distribution isotropic
- Interactions among constituents generate a pressure gradient which transforms the initial spatial anisotropy into a momentum-space anisotropy (that is observed as an azimuthal anisotropy of the outgoing particles)





- The mechanism is self quenching
  - The driving force dominate at early times
  - **Sensitive to Equation Of State at early times (t<5 fm/c)**

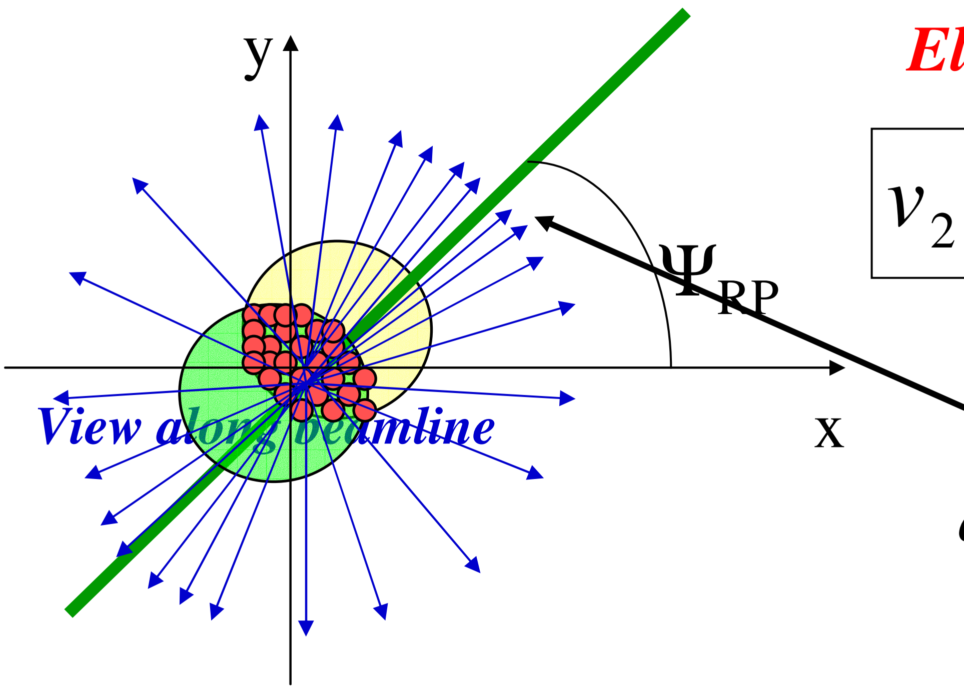
Elliptic flow coefficient v_2

- Experimentally the anisotropic transverse flow (also called elliptic flow) is measured by taking the second Fourier component of the particle azimuthal distributions relative to the reaction plane:

$$\frac{dX}{d\varphi} = \frac{X_0}{2\pi}\left(1 + 2v_1\cos(\varphi - \Psi_{RP}) + 2v_2\cos\left(2\left(\varphi - \Psi_{RP}\right)\right) + ...\right)$$

Elliptic flow coefficient

$$v_2 = \left\langle \cos\left(2\left(\varphi - \Psi_{RP}\right)\right)\right\rangle$$

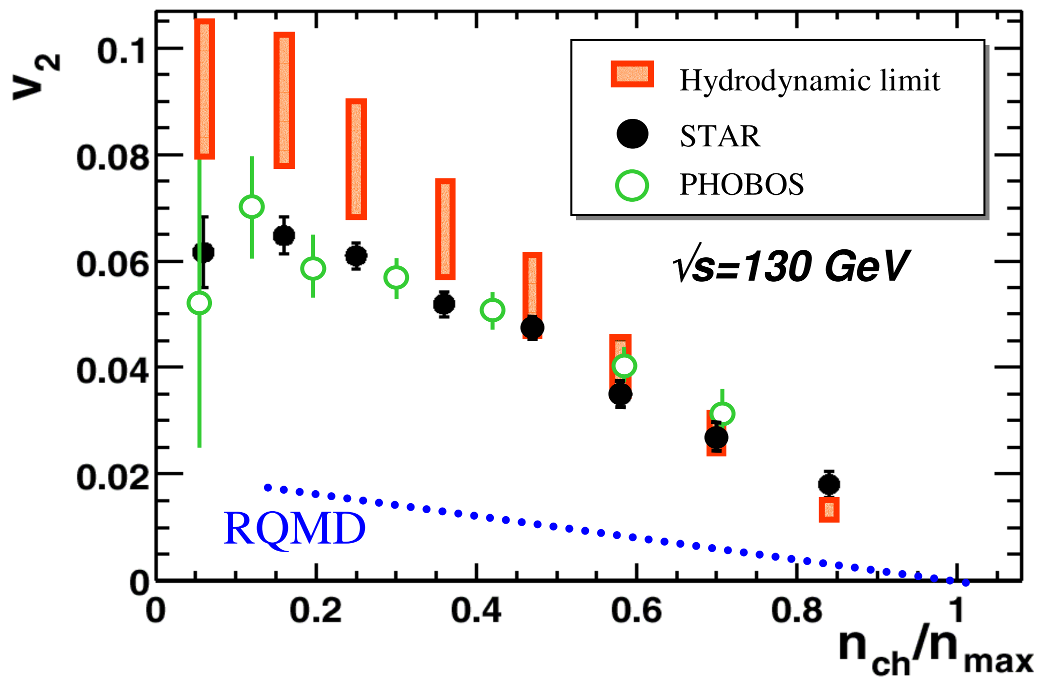


REACTION PLANE *= plane defined by beam direction and impact parameter*

v_2 versus centrality at RHIC

- Observed elliptic flow depends on:
  - Initial eccentricity (decreasing with increasing centrality)
  - Amount of rescatterings (increasing with increasing centrality)

- Measured v_2 well described by hydrodynamic model from mid-central to central collisions
  - Incomplete thermalization for peripheral collisions
  - Hint for rapid and complete thermalization for mid-central and central collisions
- Flow larger than expected from hadronic cascade models (like RQMD):
  - Evidence for a **strongly interacting (partonic) phase**

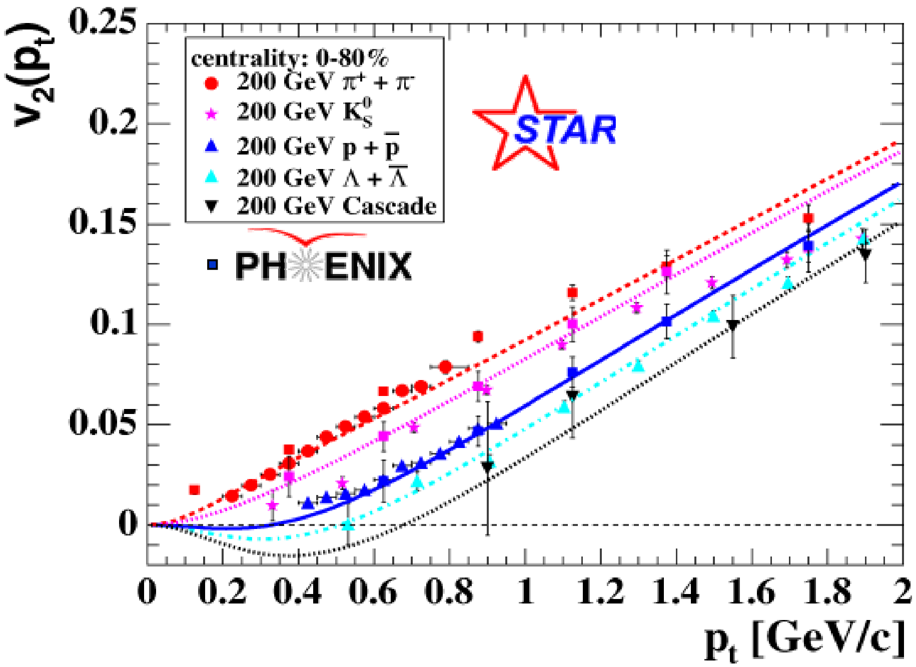


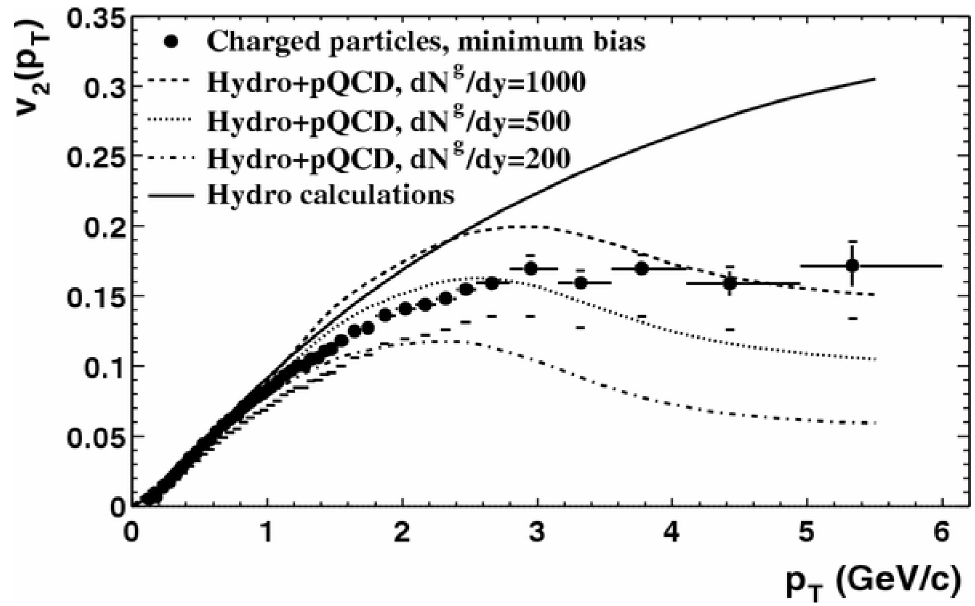
📖 *STAR: Phys. Rev. Lett. 86 (2001) 402.*

📖 *PHOBOS: Phys. Rev. Lett. 89 (2002) 222301.*

v_2 versus p_T at RHIC

STAR: *Phys.Rev.Lett. 90 (2003) 032301.*



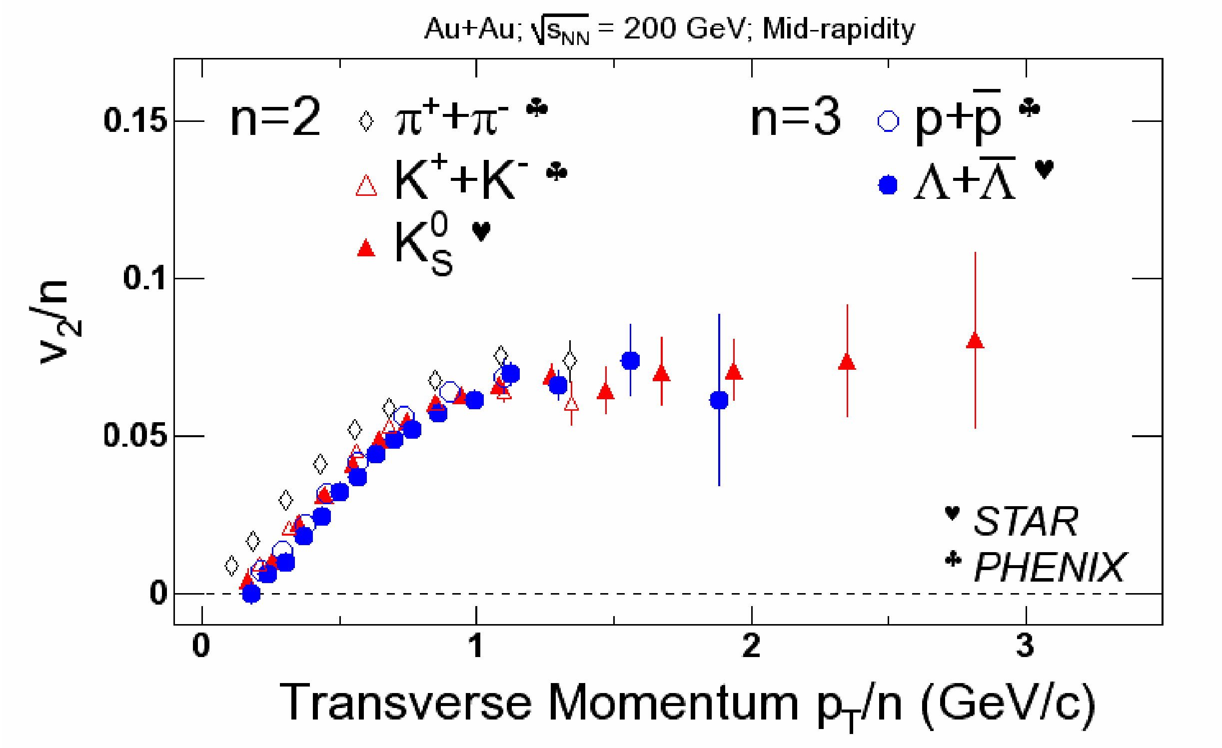


At low transverse momenta the elliptic flow is well described by ***hydrodynamical models incorporating a softening of the Equation of State*** due to quark and gluon degrees of freedom

Deviations at high p_T where:

- Hydrodynamics not applicable because high p_T partons have not undergone sufficient re-scatterings to come to thermal equilibrium
- Parton energy loss in the opaque medium is a source of anisotropy

Hadron v_2 and quark recombination



Complicated pattern of v_2 at higher p_T:

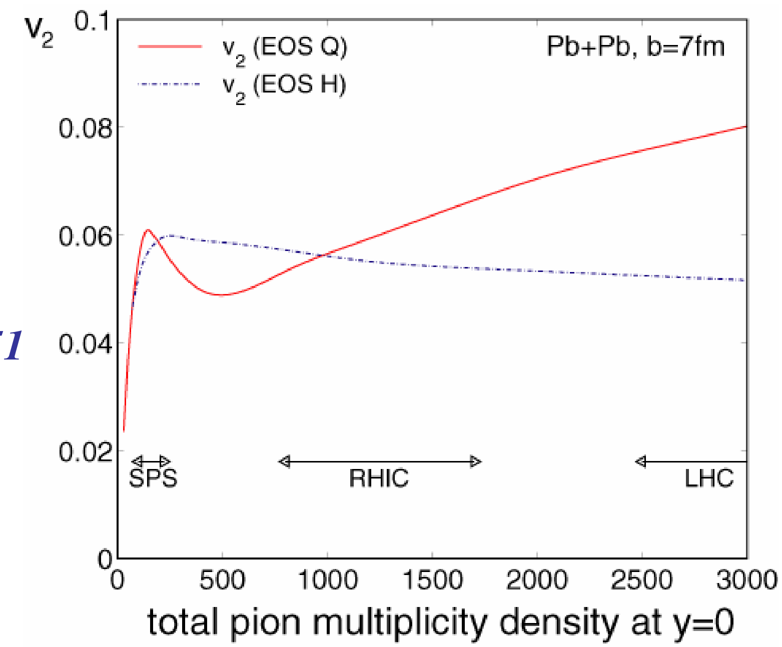
- lighter mesons deviate from hydrodynamics at $p_T \sim 1$ GeV/c
- heavier baryons deviate at significantly higher p_T
- baryons have higher v_2 values than mesons at the highest p_T measured

When v_2 is plotted per quark (v_2/n) (n=3 for baryons, and 2 for mesons) the values of v_2/n scales with p_T/n .

- Recombination model works nicely also for v_2
- Evidence for **early collective flow at the quark level !!!**

Elliptic flow at the LHC

- Multiplicity larger than at RHIC
  - by a factor 1.5-2
- v_2/ε expected larger than at RHIC
  - Few predictions:
    - 🕮 *Teaney, Shuryak, Phys.Rev.Lett. 83 (1999) 4951*
    - 🕮 *Kolb, Sollfrank, Heinz, Phys.Rev. C62 (2000) 054909.*
    - 🕮 *Bhalerao et al., Phys.Lett. B627 (2005) 49*
- Large flow values 5-10% are expected



At LHC, contribution from hydrodin. flow in the QGP phase (down to chemical freezout) much larger than at RHIC

Easier measurement (feasible on day 1 !!)
BUT: larger non-flow contribution from jets could obscure the flow signal
Important to compare different methods

Experimental methods to estimate v_n

F. Prino

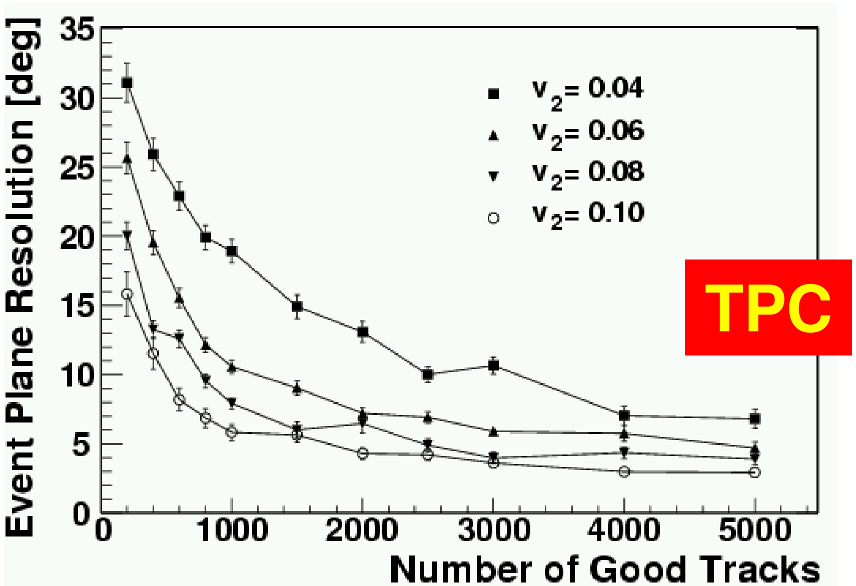
- Event plane method *(Poskanzer and Voloshin, Phys. Rev. C58 (1998) 1671.)*
  - ✓ ***Calculate an estimator of the reaction plane (EVENT PLANE) from the anisotropy of particle azimuthal distributions***
  - ✓ ***Correlate azimuth of each particle with the event plane calculated with all the other particles***
  - ✓ ***WEAK POINT: assumes that the only azimuthal correlation between particles is due to their correlation to the reaction plane (i.e. to flow)***
  - ✓ ***BUT other sources of correlation (NON-FLOW) are in due to momentum conservation, resonance decays, jets + detector granularity → SYSTEMATIC UNCERTAINTY***
- Two particle correlations *(S. Wang et al, Phys. Rev. C44 (1991) 1091.)*
  - ✓ ***No need for event plane determination***
  - ✓ ***Calculate two-particle correlations for all possible pairs of particles***
  - ✓ ***WEAK POINT: same bias from non-flow correlations as in event-plane method***
- "Cumulants" method *(Borghini et al, Phys Rev C 63 (2001) 054906.)*
  - ✓ ***Extract v_n from multi-particle azimuthal correlations***
  - ✓ ***Based on the fact that flow correlates ALL particles in the event while non-flow effects typically induce FEW-particle correlations***
  - ✓ ***DRAWBACK: larger statistical error and more sensitivity to fluctuation effects***
- Lee-Yang zeroes method *(Bhalerao et al, Nucl. Phys. A727 (2003) 373.)*
  - ✓ ***Extension of cumulants method to infinite order***

Event plane method

Performance of event plane method

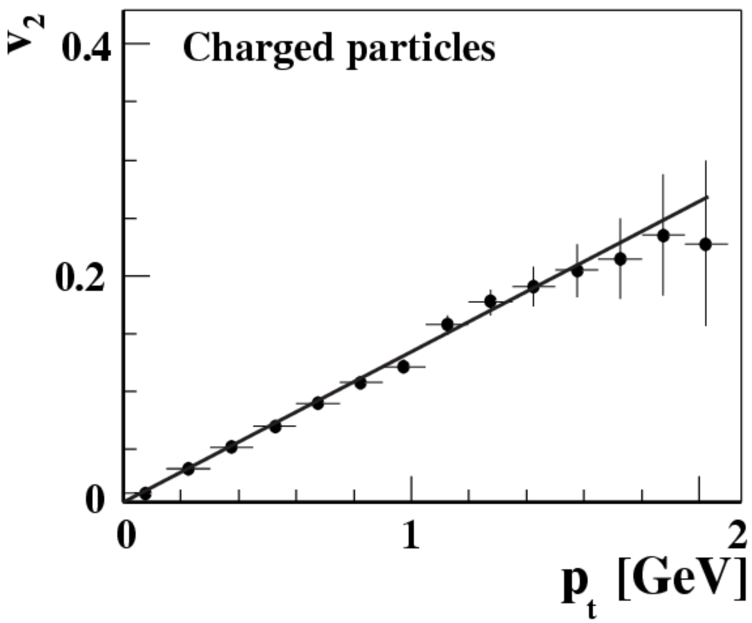
$v_n = \langle\cos[n(\phi-\phi_R)]\rangle$ / ev.plane resolution

In ALICE various independent estimates of reaction plane and v_n from track anisotropy in different regions of phase space



Measurements with:
TPC/ITS, SPD (2 layers of Silicon Pixel Detectors) and forward detectors (FMD, PMD)

- Event plane resolution depends on:
  - Amount of anisotropy (v_2)
  - Number of used tracks



Reconstructd v_2 vs. p_T for TPC tracks
- 100 Pb-Pb events
- 2000 tracks per event

Highlights on physics topics

Heavy flavours and quarkonia

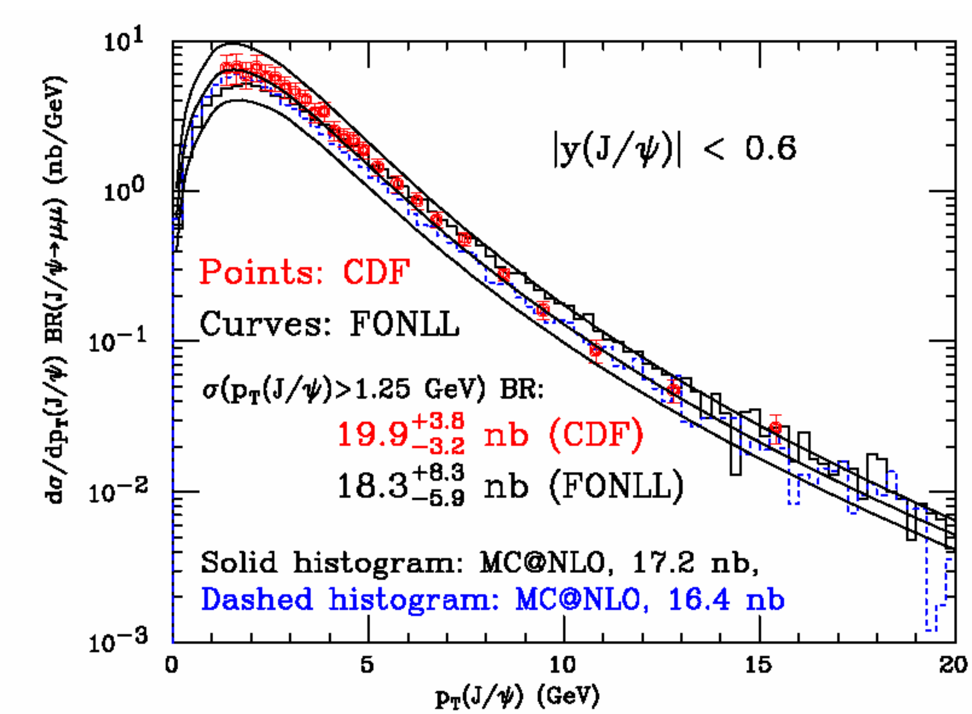
Heavy Flavour physics in ALICE: motivations

- **Energy loss of Heavy Quarks (HQ) in hot and high density medium** formed in AA central collisions.
- **Brownian motion** and **coalescence of low p_T HQ** in the quark gluon plasma (QGP).
- **Dissociation (and regeneration) of quarkonia in hot QGP**.
- Heavy flavour physics in **pp collisions**: small x physics, pQCD, HQ fragmentation functions, gluon shadowing, quarkonia production mechanism.

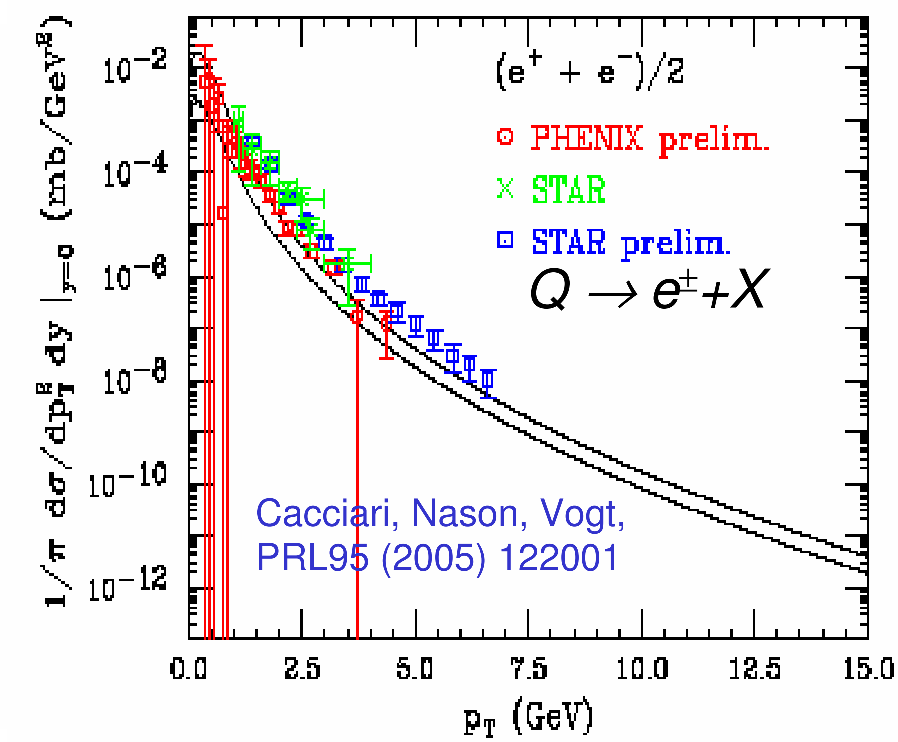
c and b production in pp at the LHC

Important test of pQCD in a new energy domain (14 TeV)

- At Tevatron (1.96 TeV) B production is well described by a FONLL calculation of $\hat{\sigma}$
- But… charm production is still underpredicted at Tevatron (1.96TeV) and at RHIC (200 GeV)



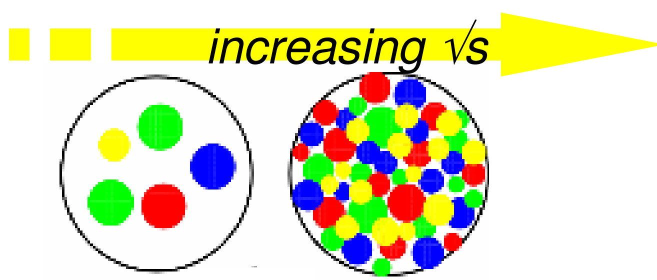
Cacciari, Frixione, Mangano, Nason and Ridolfi, JHEP0407 (2004) 033

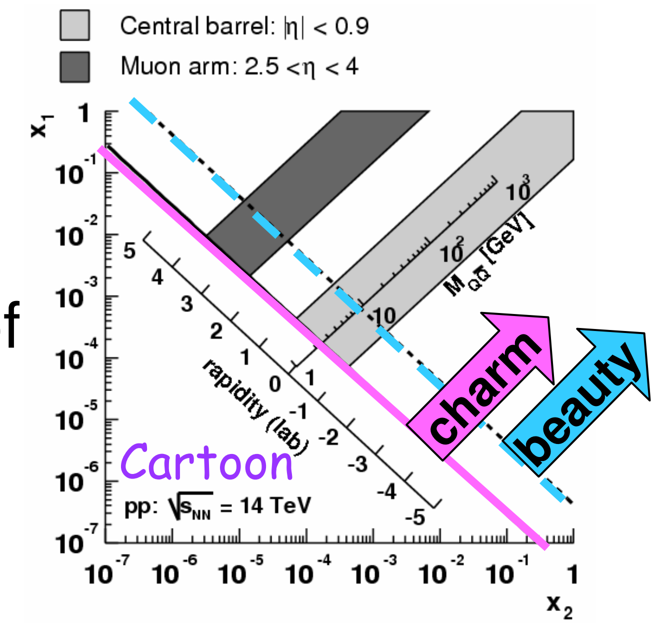


Cacciari, Nason, Vogt, PRL95 (2005) 122001

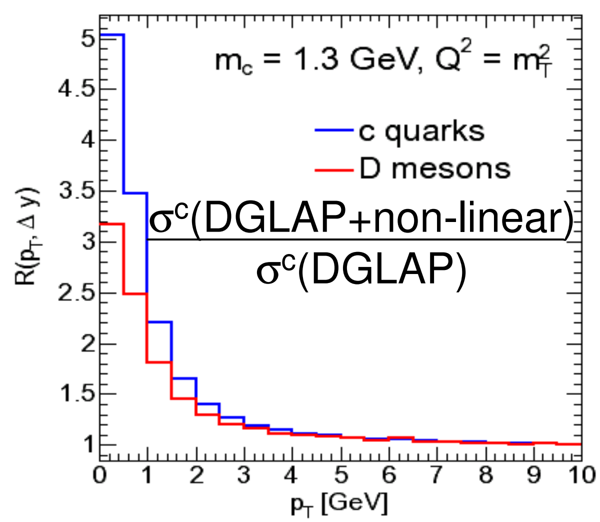
Heavy quarks as a probe of small-x gluons

- Probe unexplored small-x region with HQs at low p_t and/or forward y
  - down to x~10^{-4} with charm already at y=0
- Window on the rich phenomenology of high-density PDFs
  - gluon saturation / recombination effects
  - non-linear terms in PDFs evolution





- Possible effect: enhancement of charm production at **low p_t** w.r.t. to standard DGLAP-based predictions



Eskola, Kolhinen, Vogt, PLB582 (2004) 157
Gotsmann, Levin, Maor, Naftali, hep-ph/0504040

A. Dainese

c and b production in A-A collisions at the LHC

- Hard primary production in parton processes (pQCD)
  - Binary scaling for hard process yield:

$$\mathrm{d}N_{AA} / \mathrm{d}p_T = N_{coll} \times \mathrm{d}N_{pp} / \mathrm{d}p_T$$

- Baseline predictions for charm / beauty:

  NLO (MNR code) in pp + binary scaling (shadowing included for PDFs in the Pb)

system : $\sqrt{s_{NN}}$:	Pb-Pb (0-5% centr.) 5.5 TeV	p-Pb (min. bias) 8.8 TeV	pp 14 TeV
$\sigma_{NN}^{Q\bar{Q}}$ [mb]	4.3 / 0.2	7.2 / 0.3	11.2 / 0.5
$N_{tot}^{Q\bar{Q}}$	115 / 4.6	0.8 / 0.03	0.16 / 0.007
$C_{shadowing}^{EKS98}$	0.65 / 0.80	0.84 / 0.90	--

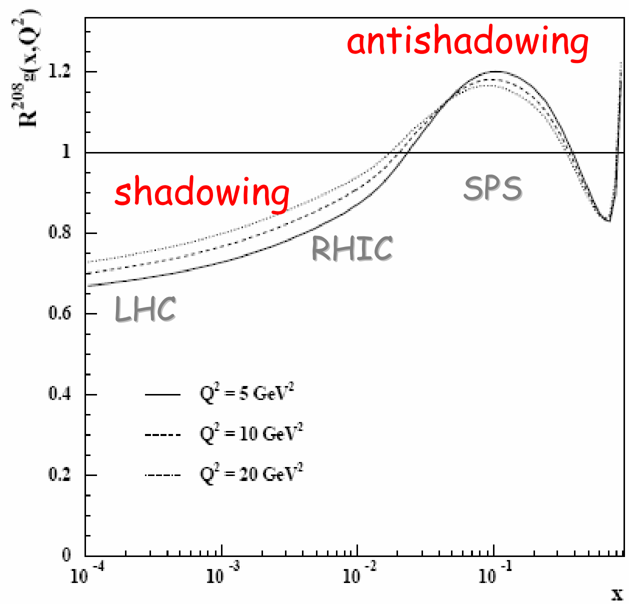
$$\sigma_{LHC}^{c\bar{c}} \approx 10 - 20 \times \sigma_{RHIC}^{c\bar{c}} \;!!$$

- Secondary (thermal) c-cbar production in the QGP
  - m_c (≈1.2 GeV) only 10%-50% higher than predicted temperature of QGP at the LHC (500-800 MeV)
  - Thermal yield expected much smaller than hard primary production

Violation of binary scaling in A-A collisions

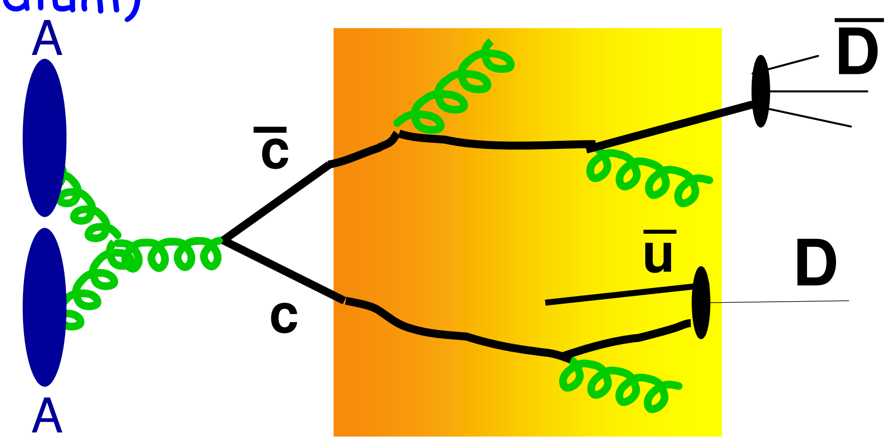
- Initial state effects
  - PDFs in nucleus different from PDFs in nucleon
    - ✓ ***Anti-shadowing and shadowing***
  - k_T broadening (Cronin effect)
  - Parton saturation (Color Glass Condensate)

Present also in pA (dA) collisions
Concentrated at lower p_T



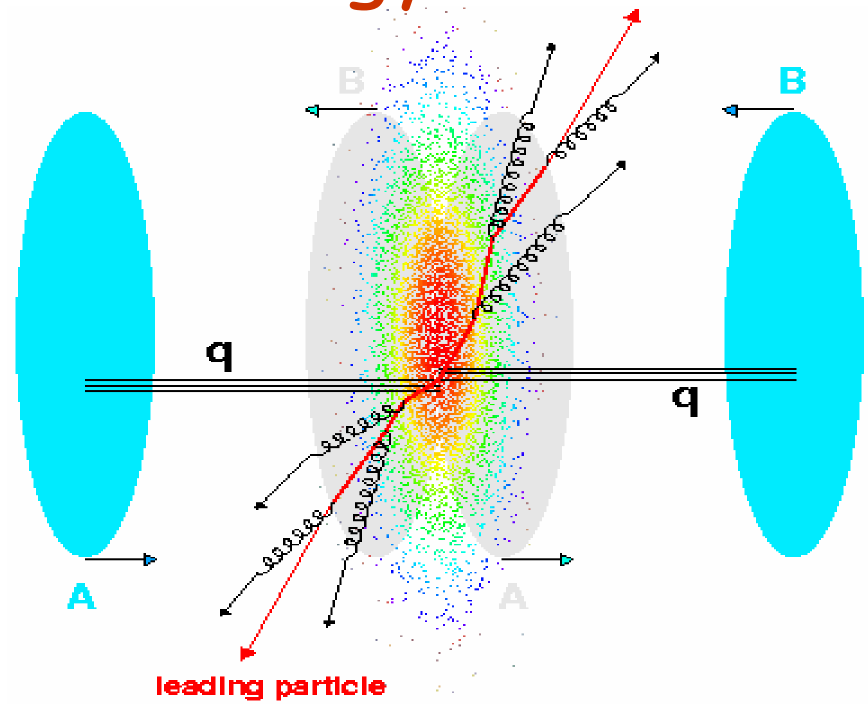
- Final state effects (due to the medium)
  - Energy loss
    - ✓ ***Mainly by gluon radiation***
  - In medium hadronization
    - ✓ ***Recombination vs. fragmentation***

Only in AA collisions
Dominant at higher p_T



Pb-Pb collisions: parton energy loss

- **Partons travel ~ 4 fm in the high colour-density medium**
- **Energy loss (*gluon radiation* + collisional?)**



$$\langle \Delta E \rangle \propto \alpha_s \, C_R \, \hat{q} \, L^2$$ (BDMPS)

Casimir coupling factor:
4/3 for quarks
3 for gluons

Medium transport coefficient
$\propto$ gluon density

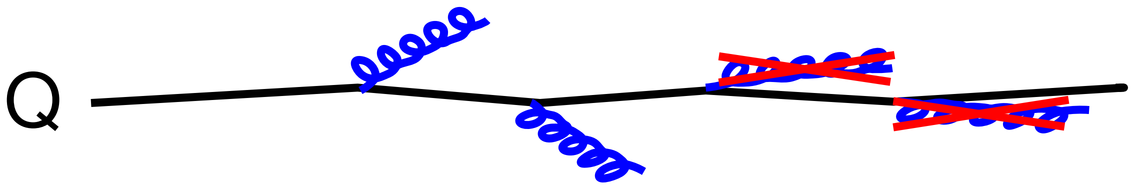
Probe the medium

Baier, Dokshitzer, Mueller, Peigne', Schiff, (BDMPS), NPB483 (1997) 291

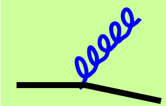
Lower E loss for heavy quarks?

- In vacuum, gluon radiation suppressed at $\theta < m_Q/E_Q$

  → **"dead cone" effect**



Gluonstrahlung probability



$$\propto \frac{1}{[\theta^2 + (m_Q / E_Q)^2]^2}$$

- *Dead cone implies lower energy loss* (Dokshitzer-Kharzeev, 2001)
- Detailed calculation confirms this qualitative feature, although effect is small and uncertainties significant (Armesto-Salgado-Wiedemann, 2003)

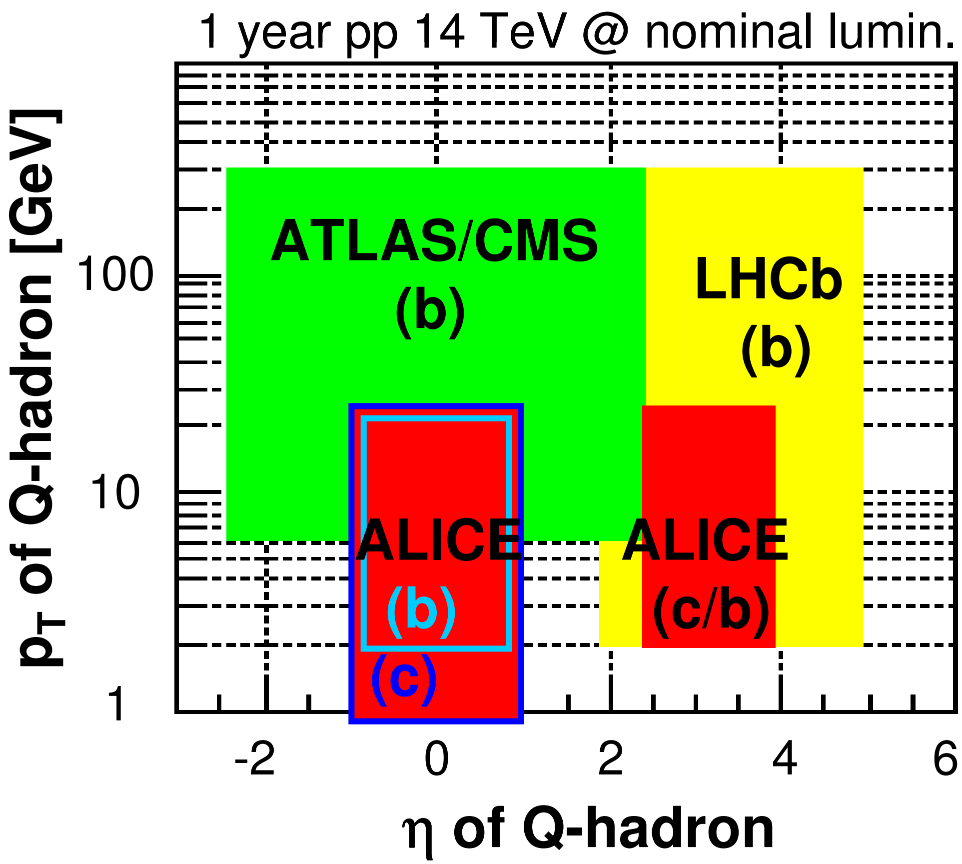
➡ Exploit abundant massive probes at LHC & study the effect by measuring the nuclear modification factor for D and B

$$R_{AA}^{D,B}(p_t) = \frac{1}{N_{coll}} \times \frac{dN_{AA}^{D,B} / dp_t}{dN_{pp}^{D,B} / dp_t}$$

Dokshitzer, Kharzeev, PLB519 (2001) 199
Armesto, Salgado, Wiedemann, PRD69 (2004) 114003

Heavy-flavours in ALICE

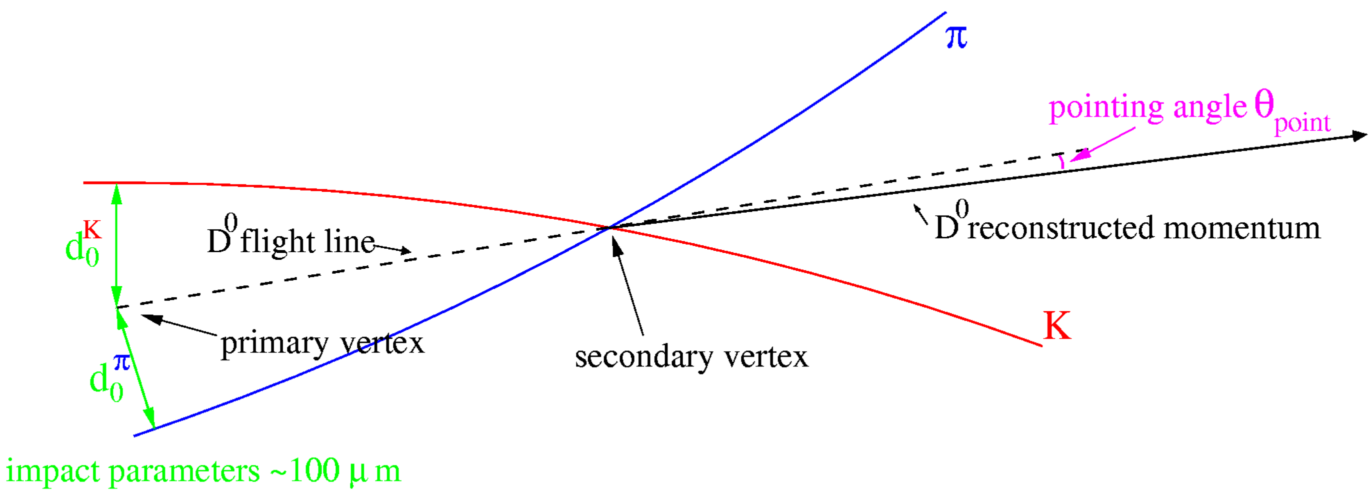
- ALICE can study several channels:
  - hadronic (|η|<0.9)
  - electronic (|η|<0.9)
  - muonic (2.5 < η < 4)
- ALICE coverage:
  - low-p_T region (down to $p_t \sim 0$ for charm)
  - central and forward rapidity regions
- High precision vertexing in the central region to identify D ($c\tau \sim$ 100-300 μm) and B ($c\tau \sim$ 500 μm) decays



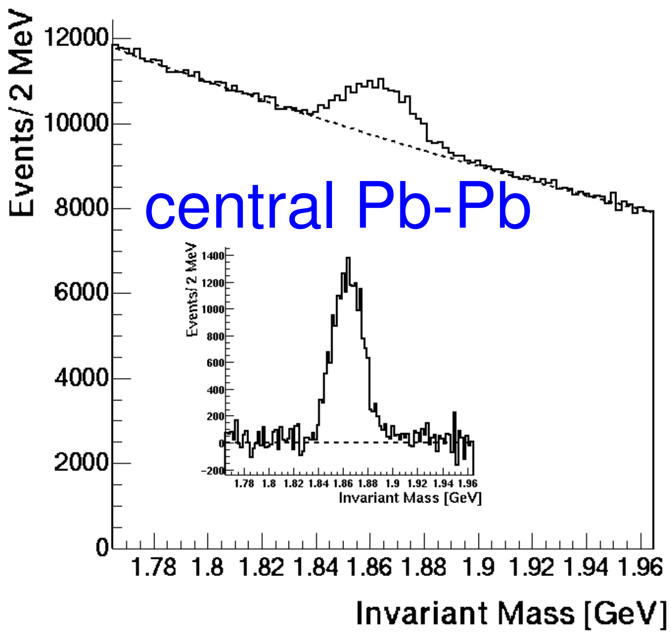
Hadronic decays of D mesons

- **No dedicated trigger in the central barrel** → extract the signal from Minimum Bias events
  - Large combinatorial background (benchmark study with $dN_{ch}/dy = 6000$ in central Pb-Pb!)
- **SELECTION STRATEGY**: invariant-mass analysis of fully-reconstructed topologies originating from **displaced vertices**
  - build pairs/triplets/quadruplets of tracks with **correct combination of charge signs** and **large impact parameters**
  - **particle identification** to tag the decay products
  - calculate the **vertex (DCA point)** of the tracks
  - requested a **good pointing** of reconstructed D momentum to the primary vertex

$D^0 \rightarrow K^- \pi^+$



$D^0 \rightarrow K^- \pi^+$: results (I)

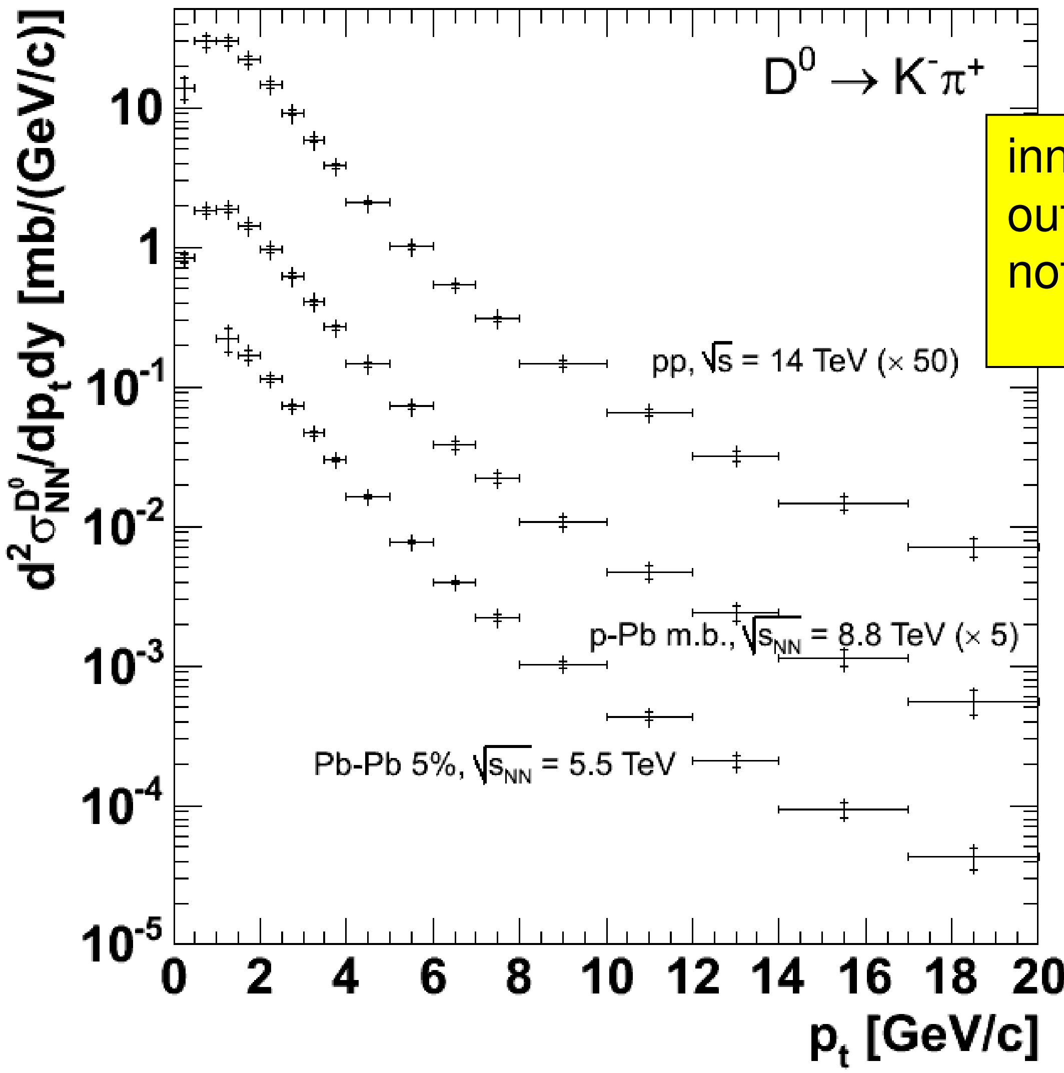


	S/B initial (M±3σ)	S/B final (M±1σ)	Significance $S/\sqrt{S+B}$ (M±1σ)
Pb-Pb Central (dN_{ch}/dy = 6000)	$5 \cdot 10^{-6}$	**10%**	**~35 (for 10^7 evts*)**
pPb min. bias	$2 \cdot 10^{-3}$	**5%**	**~30 (for 10^8 evts)**
pp	$2 \cdot 10^{-3}$	**10%**	**~40 (for 10^9 evts)**

However, with dN_{ch}/dy = 3000 in Pb-Pb, S/B larger by × 4 and significance larger by × 2

* 1 year at nominal luminosity:
10^7 central Pb-Pb events (1 month run, central events are 10% of total rate),
10^9 pp events (7 months run) and 10^8 p-Pb events (1 month run)

$D^0 \rightarrow K^-\pi^+$: results (II)



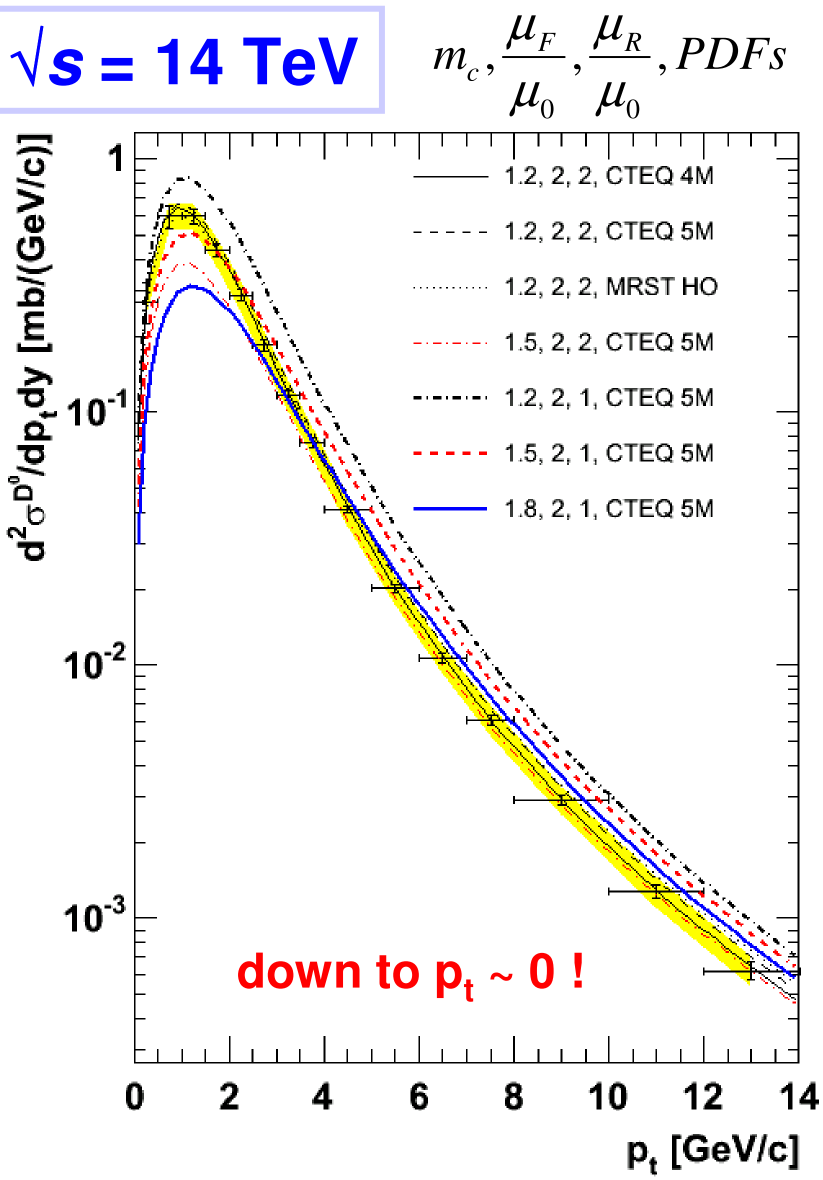
inner bars: stat. errors
outer bars: stat. ⊕ p_t-dep. syst.
not shown: 9% (Pb-Pb), 5% (pp, p-Pb) normalization errors

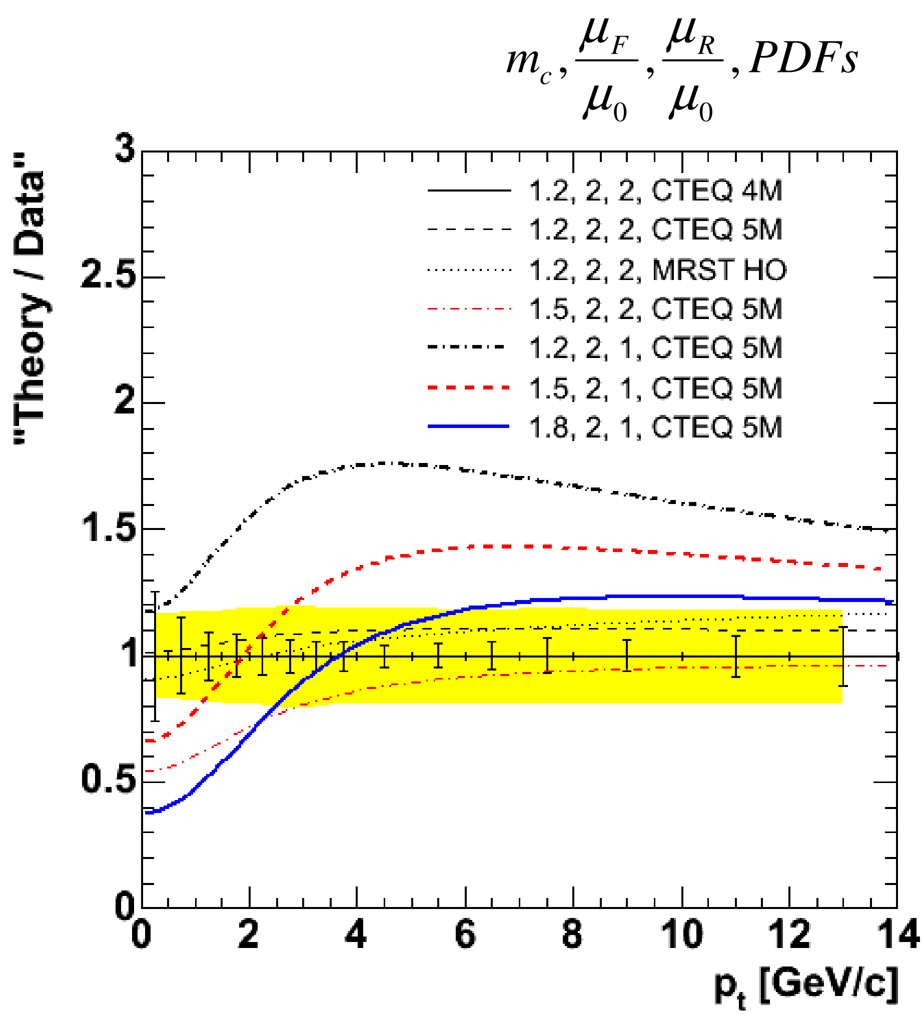
1 year at nominal luminosity:
10^7 central Pb-Pb events,
10^9 pp events and
10^8 p-Pb events

➡ Down to p_t ~ 0 in pp and p-Pb (1 GeV/c in Pb-Pb) for D^0 production cross-section measurement

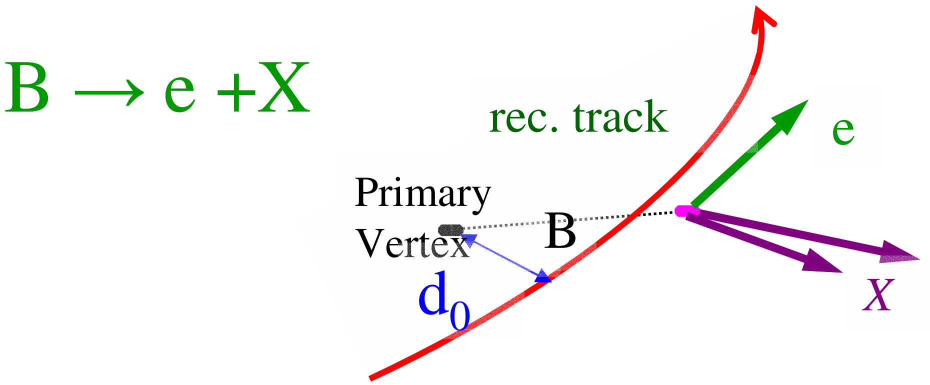
Open charm in pp ($D^0 \rightarrow K\pi$)
Sensitivity to NLO pQCD parameters

$\sqrt{s}$ = 14 TeV



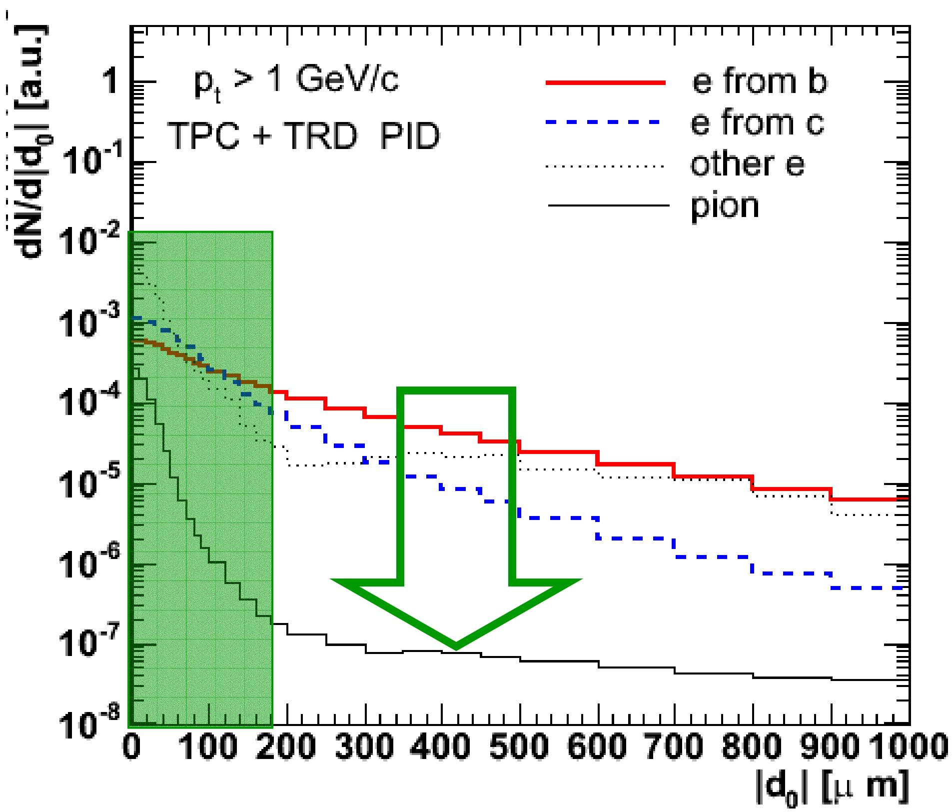


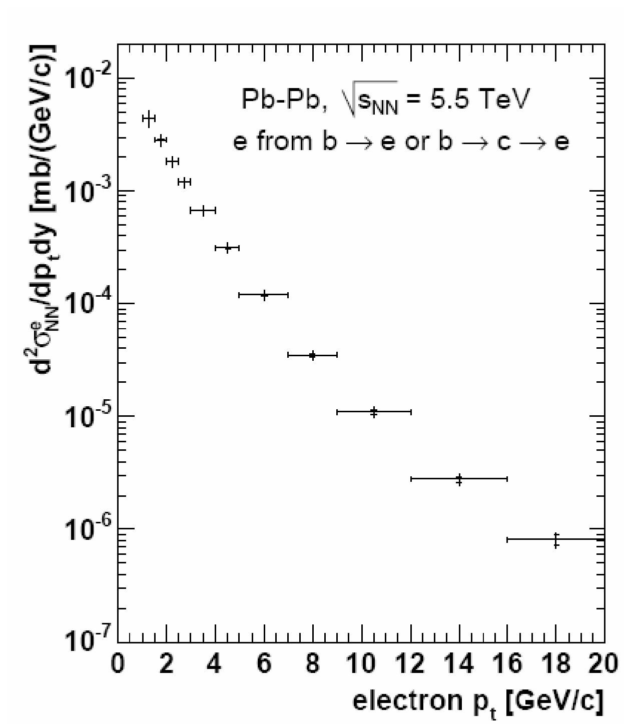
Open Beauty from single electrons



STRATEGY

- Electron Identification (TRD+TPC): reject most of the hadrons
- Impact parameter cut: high precision vertexing in ITS: reduce charm and bkg electrons
- Subtraction of the residual background

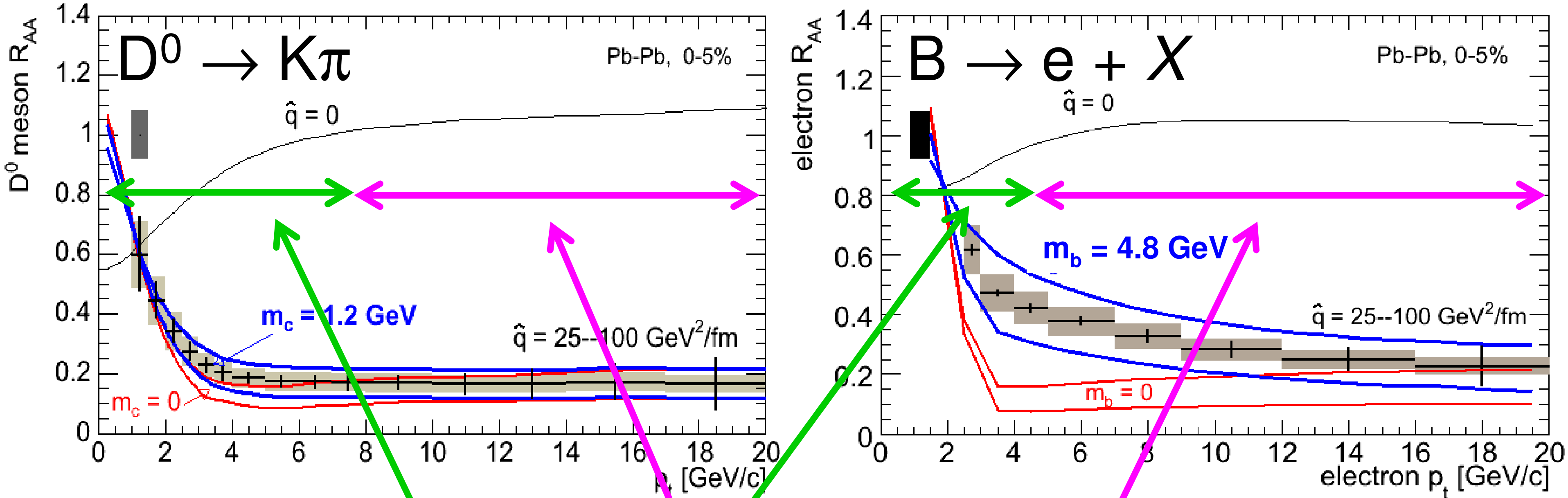




Charm and Beauty Energy Loss : R_{AA}

$$R_{AA}^{D}(p_t) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}^{D}/dp_t}{dN_{pp}^{D}/dp_t}$$

$$R_{AA}^{e}(p_t) = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{AA}^{e}/dp_t}{dN_{pp}^{e}/dp_t}$$



Low p_t (< 6–7 GeV/c)

Also nuclear shadowing (here EKS98)

High p_t (> 6–7 GeV/c)

Only parton energy loss

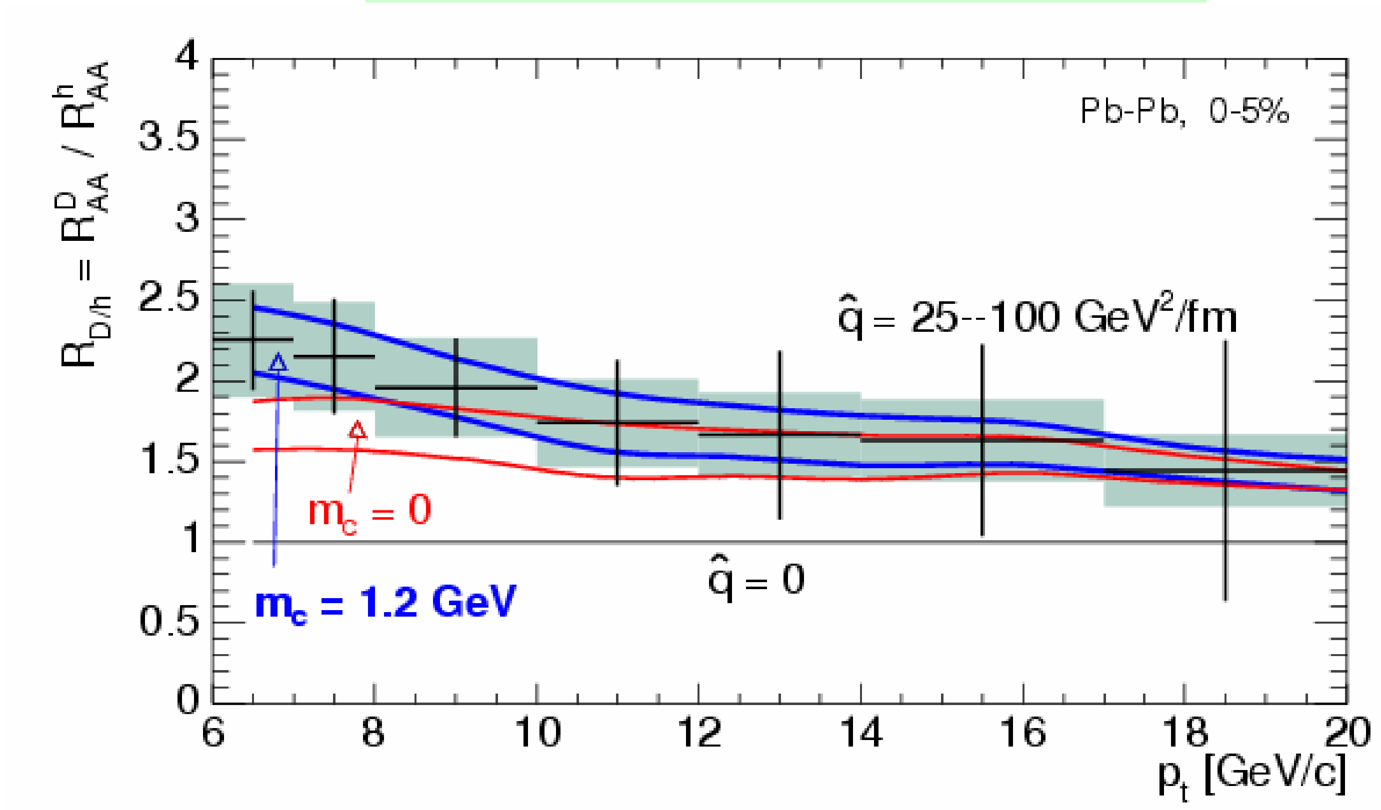
1 year at nominal luminosity

(10^7 central Pb-Pb events, 10^9 pp events)

Heavy-to-light ratios in ALICE

For charm:

$$R_{D/h}(p_t) = R_{AA}^{D}(p_t) / R_{AA}^{h}(p_t)$$

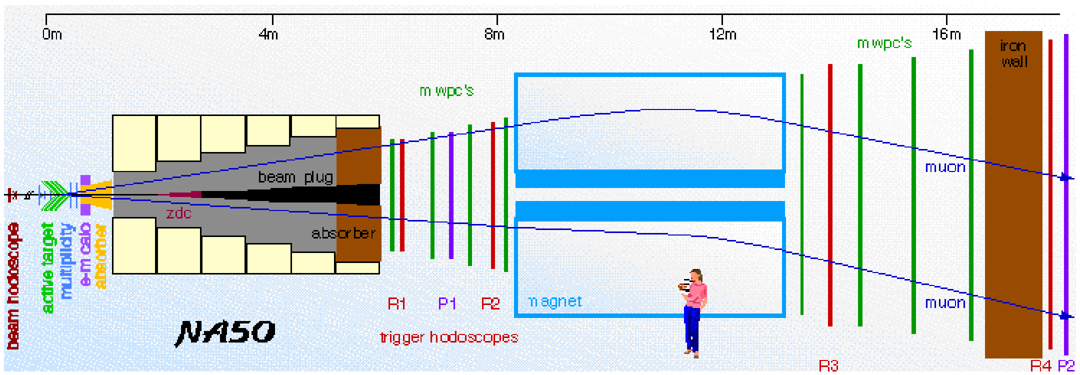


1 year at nominal luminosity
(10^7 central Pb-Pb events, 10^9 pp events)

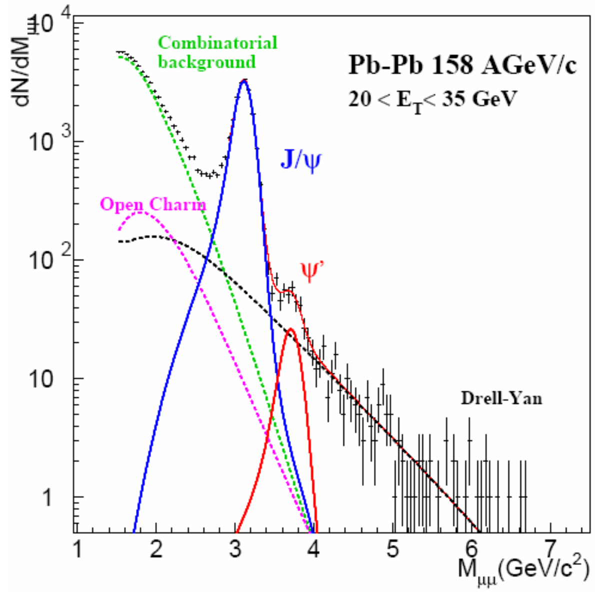
Charmonia in AA collisions: from SPS and RHIC to LHC

J/ψ measurement in NA50 at the SPS

- Aim of NA50: study the production of J/ψ in Pb-Pb collisions
- Experimental technique:
  - absorb all charged particles produced in the collision except muons
  - detect J/ψ by reconstructing the decays **$J/\psi \rightarrow \mu^+\mu^-$ (B.R. ≅ 5.9 %)**



- The **measured dimuon spectrum** is fitted to a source cocktail in order to extract the J/ψ, ψ' and Drell-Yan contributions



Quarkonium production is usually normalised to Drell-Yan production (which is not influenced by strong interactions)

J/ψ anomalous suppression in NA50

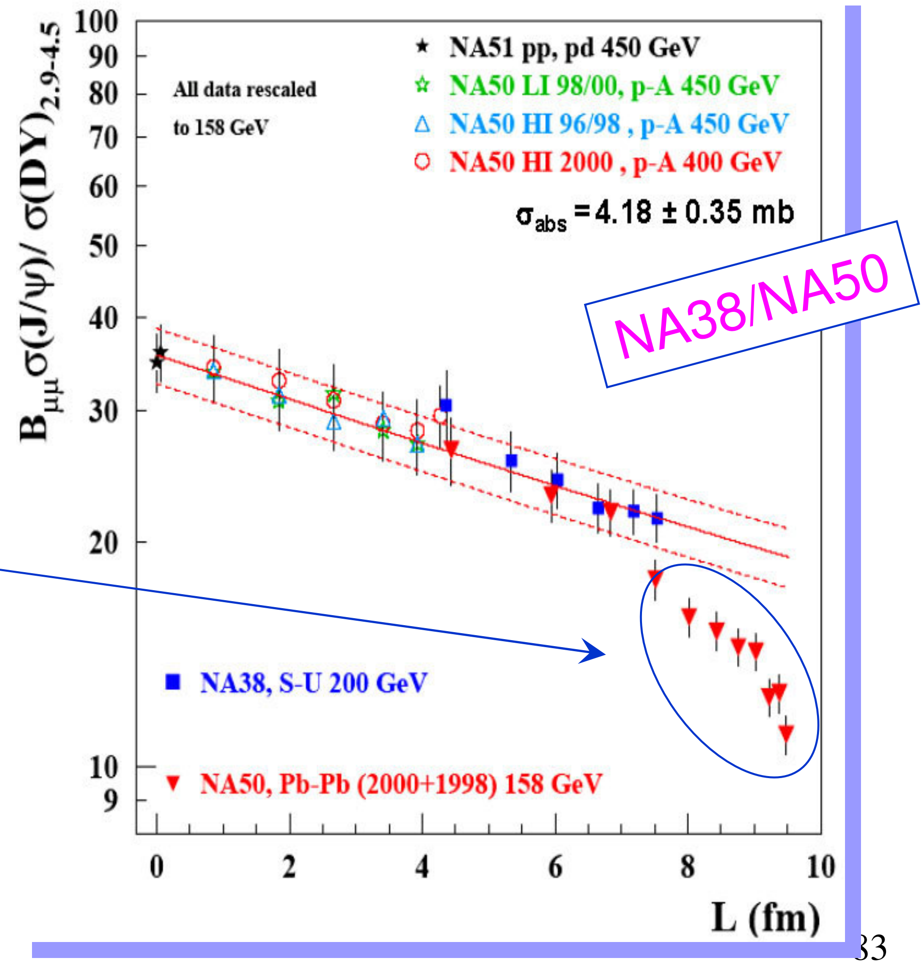
In **peripheral Pb-Pb collisions** the (J/ψ)/DY ratio is consistent with a **normal suppression pattern** (due to the absorption of a pre-resonant c-cbar state before the J/ψ formation) increasing with the centrality of the collision

In **central Pb-Pb collisions** (b < 8 - 8.5 fm) a **much stronger suppression** is observed:

Anomalous suppression

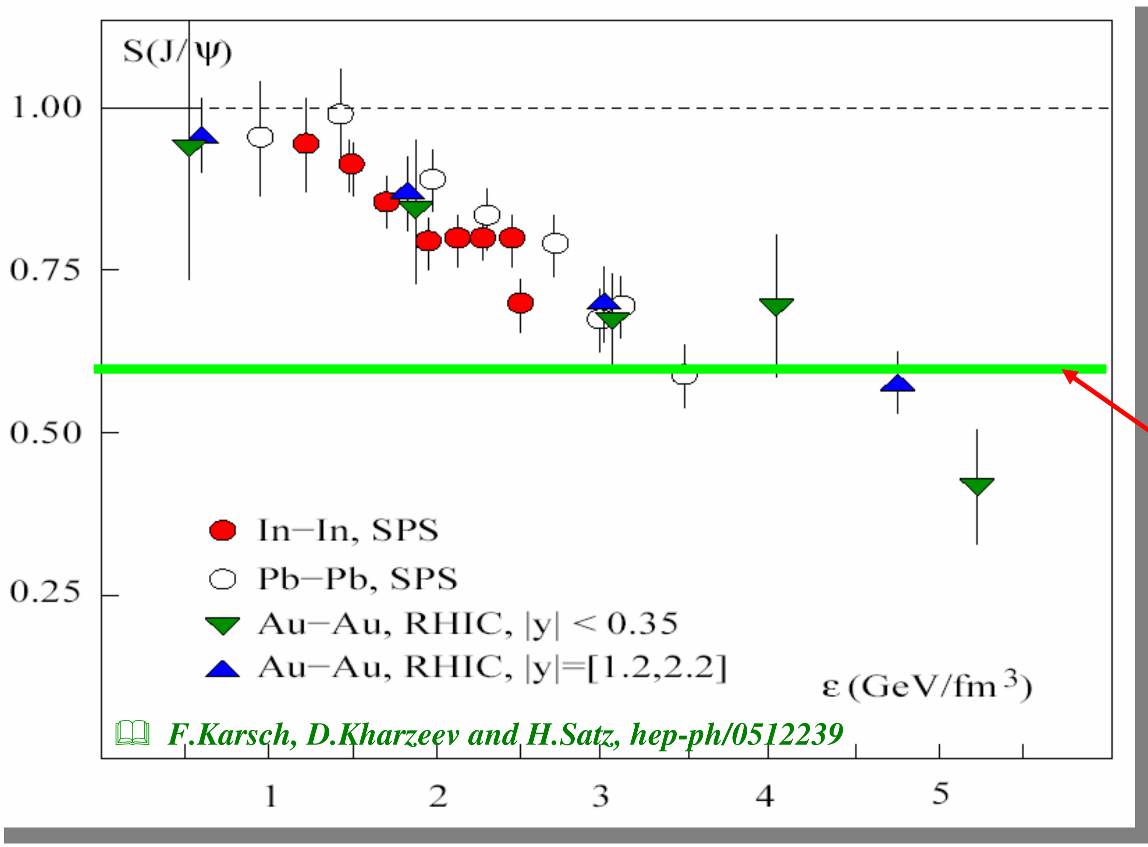
New In-In data (NA60) follow the Same pattern !!!

Anomalous suppression is the candidate as signal for deconfinement



J/ψ survival probability

S(J/ψ) = measured/expected yields (from preresonance absorption only)



Included here also the experimental results of NA60 (InIn at SPS) and PHENIX (AuAu at RHIC)

Results consistent with the full disappearance of χ_c , ψ'
$S_{\chi_c,\psi'}$ =0 and the survival of the directly produced J/ψ
$S^{dir}_{J/\psi}$ =1

If we take into account the fraction (~60%) of the observed J/ψ which are not directly produced, but come from the decay of higher excited states (~30% from χ_c, ~10% from ψ'), we can rewrite S(J/ψ) as:

$$S_{J/\psi} = 0.6\, S^{dir}_{J/\psi} + 0.4\, S_{\chi_c,\psi'} \sim 0.6$$

Comments on J/ψ suppression at SPS and RHIC

The observed J/ψ suppression at SPS is qualitatively very similar to the pattern expected by deconfinement models.

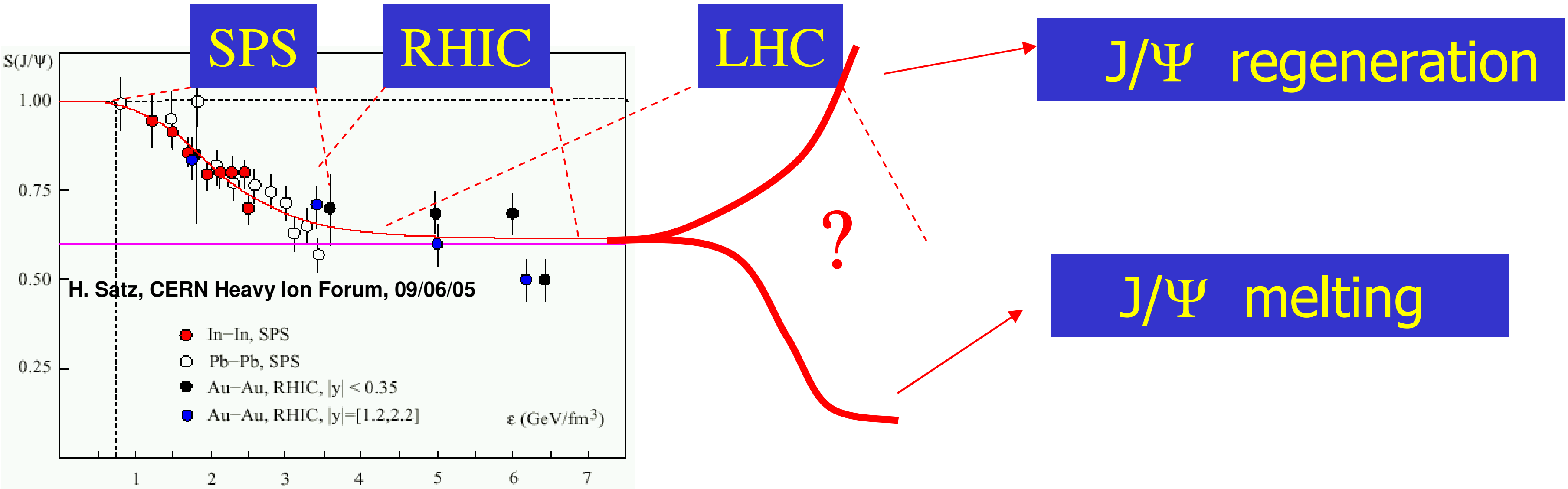
And it is consistent with the hypothesis of full disappearance of the charmonium excited states χ_c , ψ' and the survival of the directly produced J/ψ.

Recent studies of the behaviour of charmonium states in a deconfined medium show that the charmonium ground state J/ψ survives up to 1.5 -2 T_c (corresponding to a much higher energy density than at T_c) while excited states dissolve at T_c

M Asakawa et al., Prog.Part.Nucl.Phys, 46(2001) 459
M Asakawa et al. ,PRL 92(2004) 012001
S Datta et al., Int.J.Mod.Phys. A16(2001) 2215
C-Y Wong, PRC 72 (2005) 034906
W Alberico et al., PRD 72 (2005) 114011

At RHIC the J/ψ suppression is compatible with that observed at SPS. However **at RHIC in addition to the total suppression in the deconfined phase it could be allowed also the regeneration of J/ψ at hadronization by recombining c-cbar.** The agreement between SPS and RHIC data would be accidental. This scenario could also occur at LHC energies.

Charmonia in AA collisions at LHC

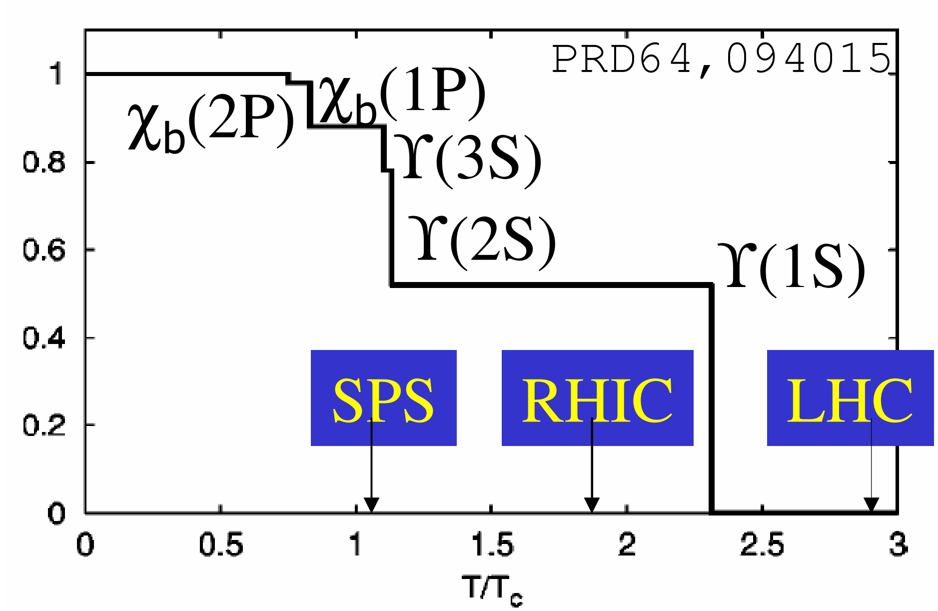


- Melting of Ψ′ and χ_c at SPS and RHIC, and melting of J/Ψ at LHC?
- Magic cancellation between J/Ψ suppression and J/Ψ regeneration?

22 (39)% of J/Ψ (Ψ′) from open beauty meson decays.

Bottomonia in AA collisions at LHC

- Regeneration is expected to be small at LHC.
- $\Upsilon(2S)$ behaves as J/ψ : $T_D^{\Upsilon(2S)} \sim T_D^{J/\psi}$
- $\Upsilon(1S)$ melts only at LHC.
- $\Upsilon(2S)/\Upsilon(1S)$ as a function of p_T.

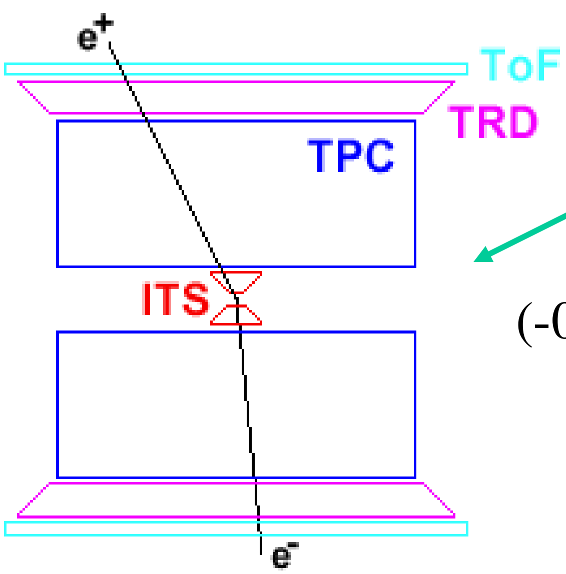


45 (30)% of feed-down from higher resonances for $\Upsilon(1S)$ ($\Upsilon(2S)$)

Heavy quarkonia in ALICE

- Identification of charmonia and bottonomia states through their dilepton decay channel both in the e^+e^- and in the $\mu^+\mu^-$ channel

- Large background from open charm & bottom
- J/ψ produced also via *b* decays
- Secondary charmonium production from kinetic recombination and statistical hadronization
- important to have good mass resolution (~ 1%) to separate the different states => perform detailed spectroscopy

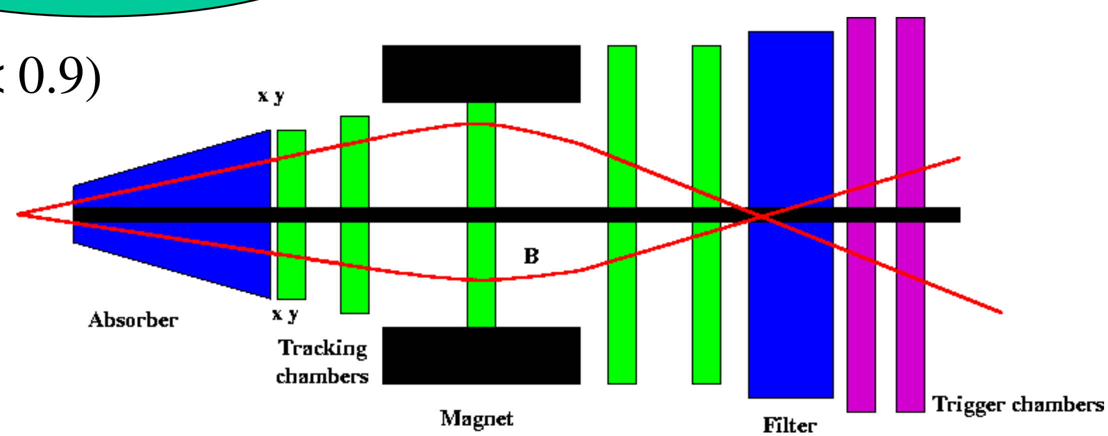


e^+e^- channel (TRD)

$(-0.9 < \eta < 0.9)$

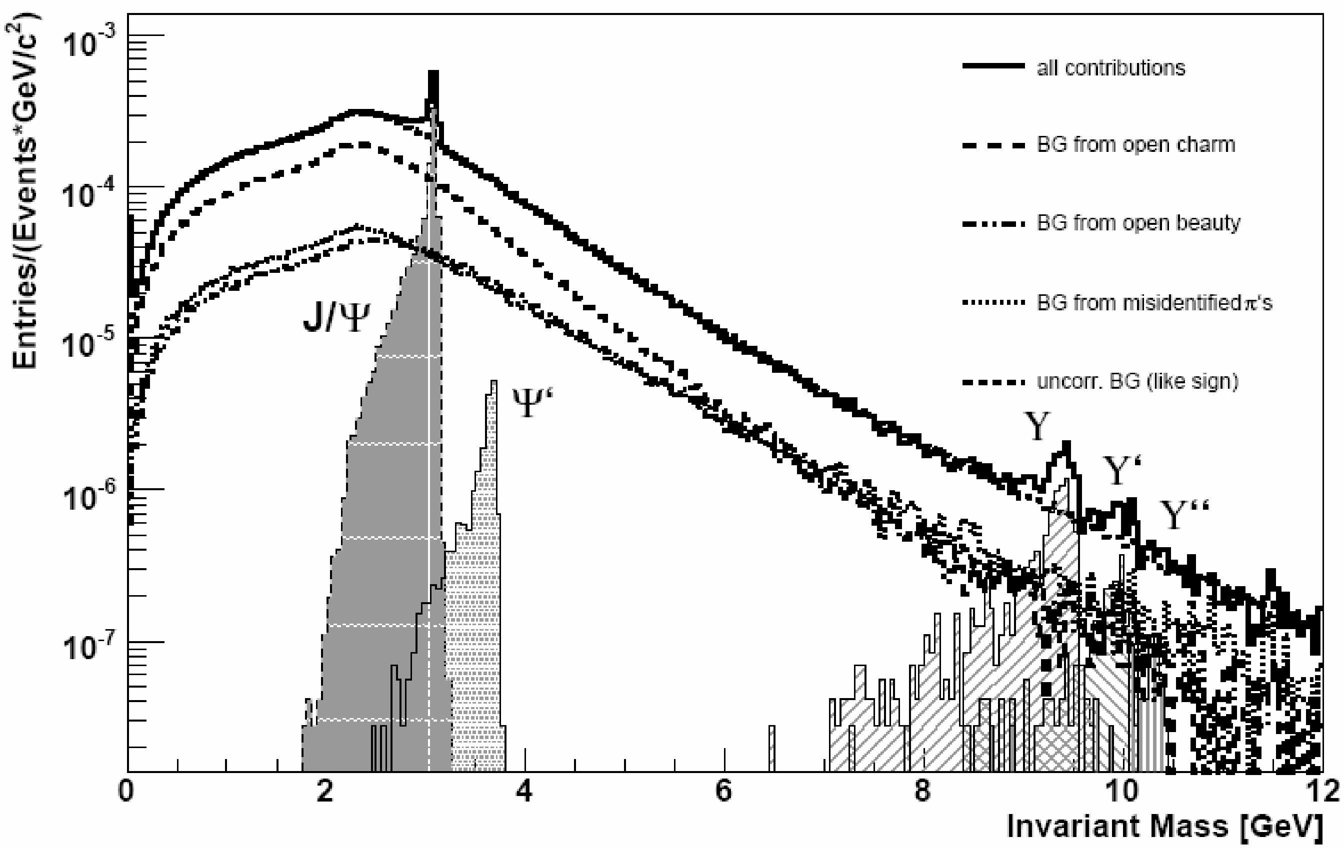
$\mu^+\mu^-$ channel (Muon arm)

$(2.5 < \eta < 4)$

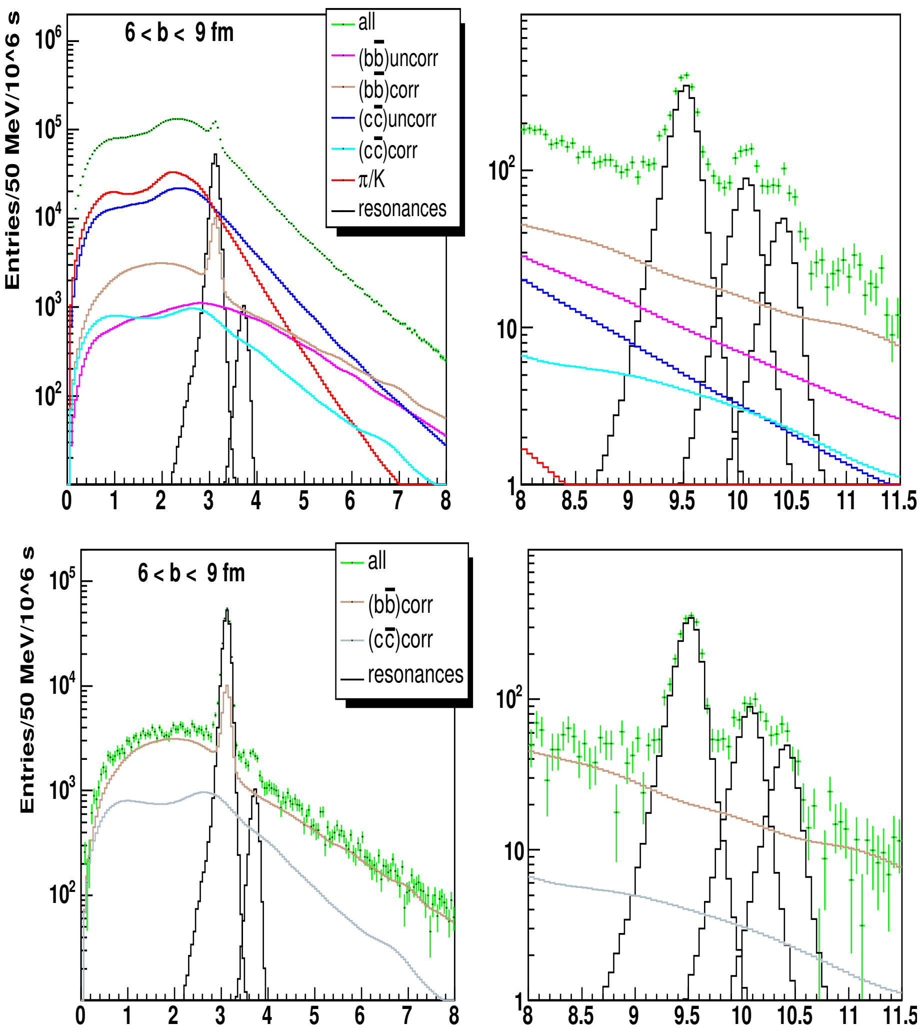


Quarkonia→e^+e^- (in PbPb with ALICE)

State	S ($\times 10^3$)	B ($\times 10^3$)	S/B	$S/\sqrt{S+B}$
J/ψ	110.7	92.1	1.2	245
Υ	0.9	0.8	1.1	21
Υ'	0.25	0.7	0.35	8



Quarkonia → $\mu^+\mu^-$ (in PbPb with ALICE)



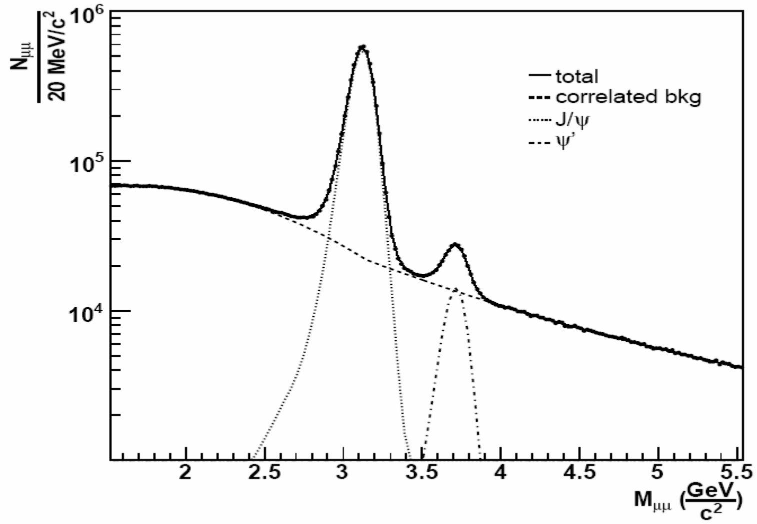
PbPb cent, 0 fm<b<3 fm

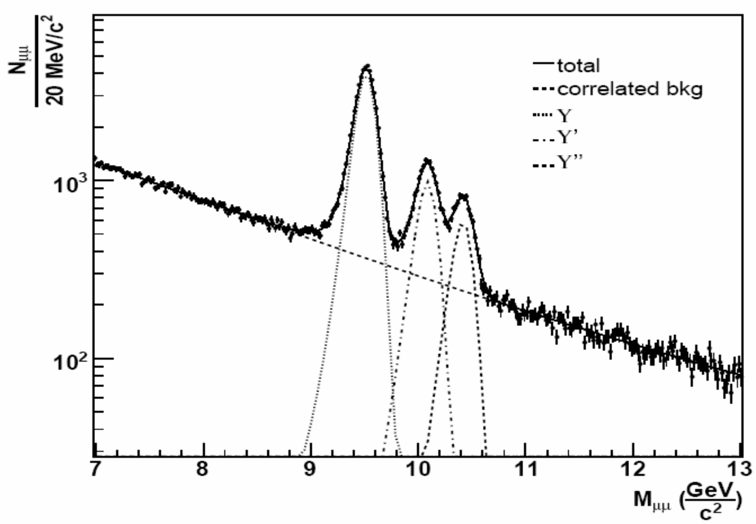
State	S[10³]	B[10³]	S/B	S/(S+B)$^{1/2}$
J/Ψ	130	680	0.20	150
Ψ’	3.7	300	0.01	6.7
ϒ(1S)	1.3	0.8	1.7	29
ϒ(2S)	0.35	0.54	0.65	12
ϒ(3S)	0.20	0.42	0.48	8.1

Yields for baseline

- ϒ(1S) & ϒ(2S) : 0-8 GeV/c
- J/Ψ high statistics: 0-20 GeV/c
- Ψ’ poor significance
- ϒ” ok, but 2-3 run will be needed.

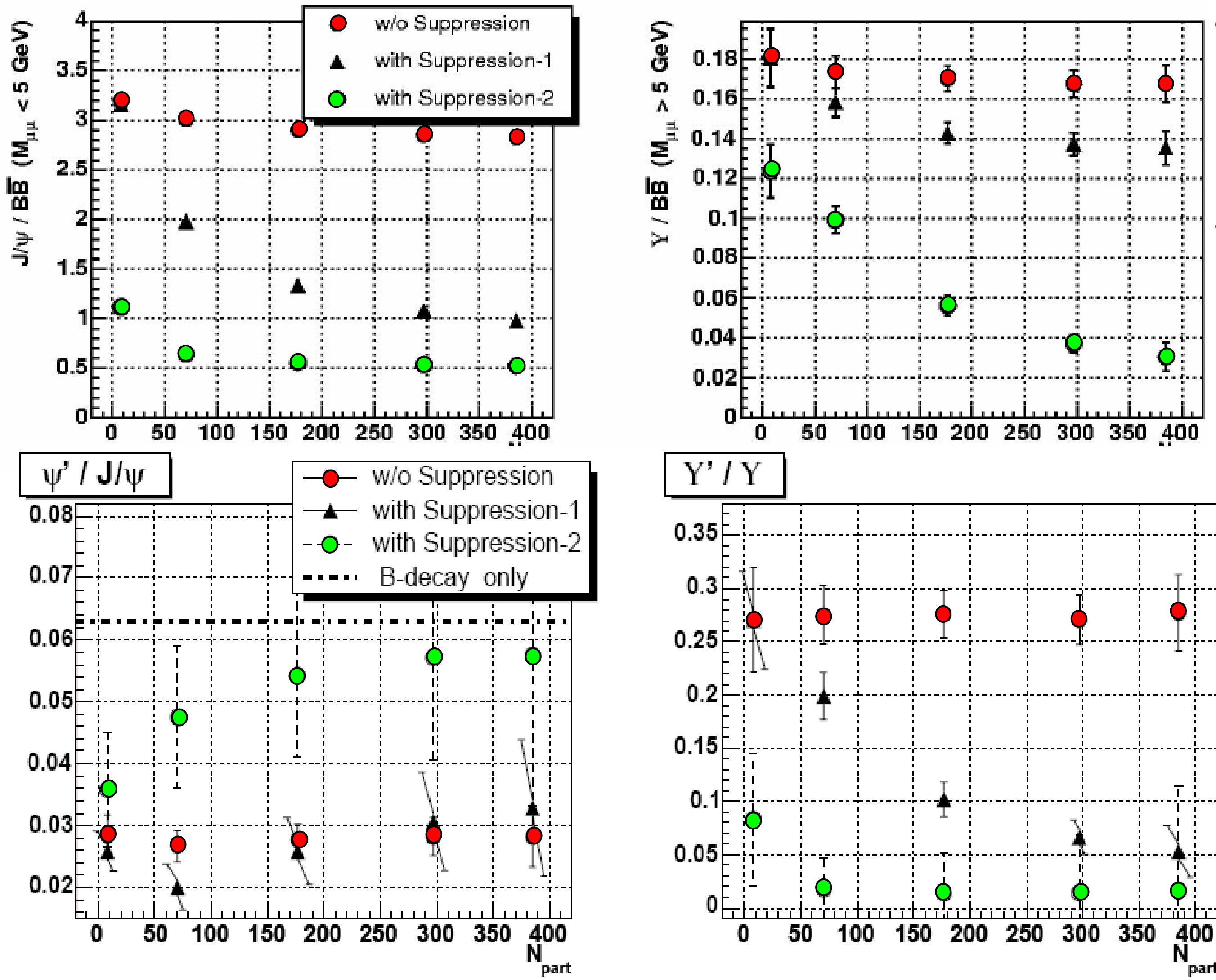
Quarkonia → $\mu^+\mu^-$ (in pp at 14 TeV with ALICE)





state	$B(\times 10^3)$	$S(\times 10^3)$	S/B	$S/\sqrt{S+B}$
J/ψ	370	4670	12.6	2081
ψ′	220	122	0.55	209
Υ	7.7	44.7	5.8	195
Υ′	6.1	11.4	1.9	86
Υ′′	5.4	6.9	1.3	62

Study of quarkonia suppression with ALICE



- Suppression-1
  - ✓ Tc =270 MeV
  - ✓ T_D/T_c=1.7 for J/Ψ
  - ✓ T_D/T_c= 4.0 for ϒ.
- Suppression-2
  - ✓ Tc=190 MeV
  - ✓ T_D/T_c=1.21 for J/Ψ
  - ✓ T_D/T_c= 2.9 for ϒ.

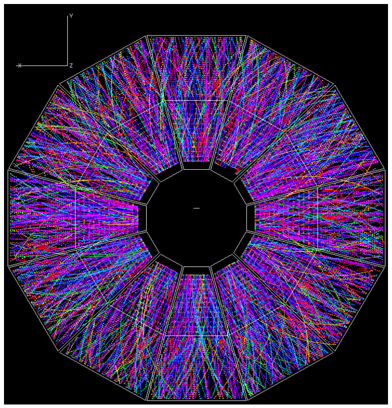
PRC72 034906(2005)
hep-ph/0507084(2005)

Good sensitivity
J/Ψ, ϒ(1S) & ϒ(2S)

Highlights on physics topics

Jet physics

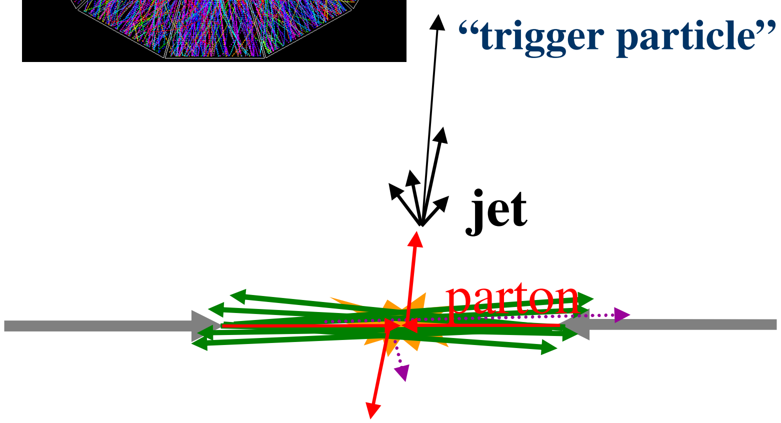
Jet studies with Heavy Ions at RHIC



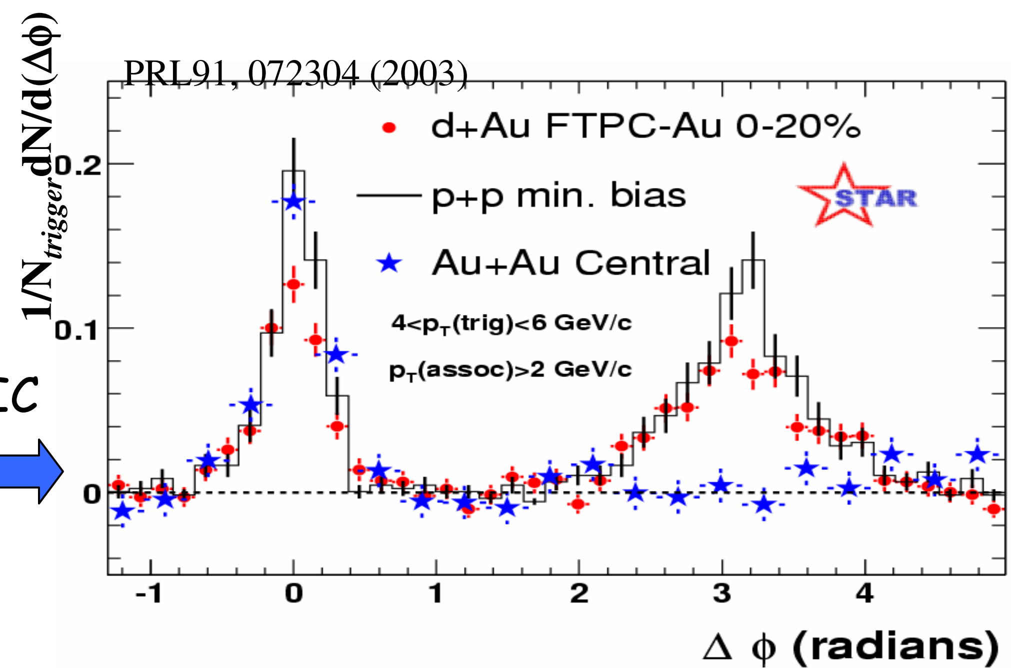
Standard jet reconstruction algorithms in nucleus-nucleus collisions **at RHIC fail** due to:

- **large energy from the underlying event** (125 GeV in R<0.7)
- limited reach up to relatively low jet energies (< 30 GeV)
- multi-jet production restricted to mini-jet region (< 2 GeV)

➡ RHIC experiments use leading particles as a probe.

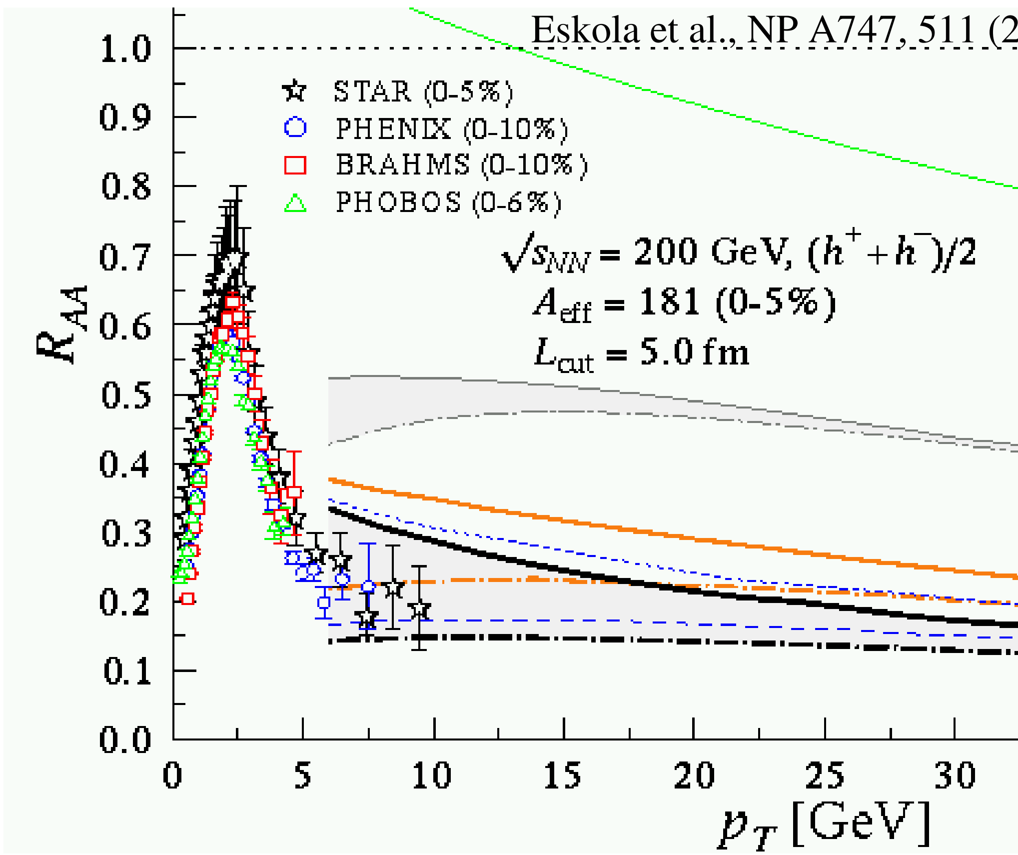


Evidence of parton energy loss at RHIC from the observed **suppression of back-to-back correlations** in Au-Au central collisions (and not in d-Au or p-p minbias). And also from the suppression of the R_{AA} ratios at high p_T



What did we learn from the R_{AA} suppression at RHIC?

- It's a ***final state effect*** (see slides: 45, 69-70)
- pQCD with energy loss calculations require initial density ~30-50 times cold nuclear matter density



$\hat{q}$ α density
(time averaged)

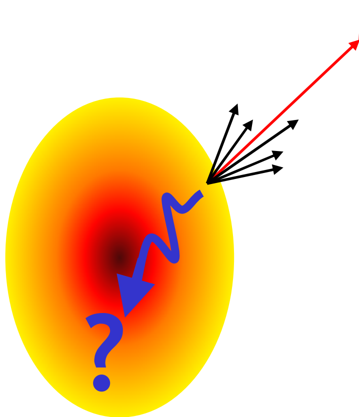
$\hat{q} = 0\,GeV^2/fm$ (no medium)

$\hat{q} = 1\,GeV^2/fm$

$\hat{q} = 5-15\,GeV^2/fm$

Leading particle versus jet reconstruction

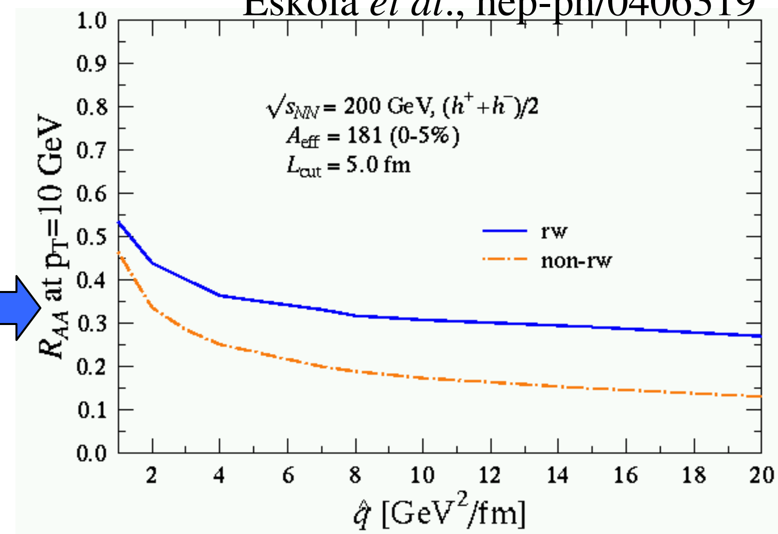
Leading Particle



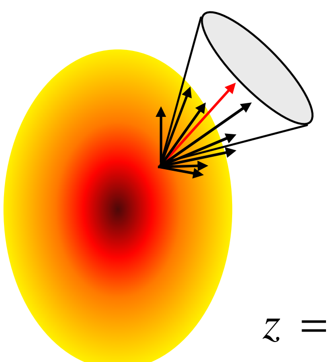
Leading particle is a fragile probe

- **Surface emission bias**
  - **Small sensitivity of R_{AA} to medium properties (at RHIC, but also at LHC)**
- For increasing in medium path length *L*, the momentum of the leading particle is less and less correlated with the original parton 4-momentum.

Eskola *et al.*, hep-ph/0406319



Reconstructed Jet



So, ideally only the **full jet reconstruction** allows to measure the original parton 4-momentum and the jet structure.

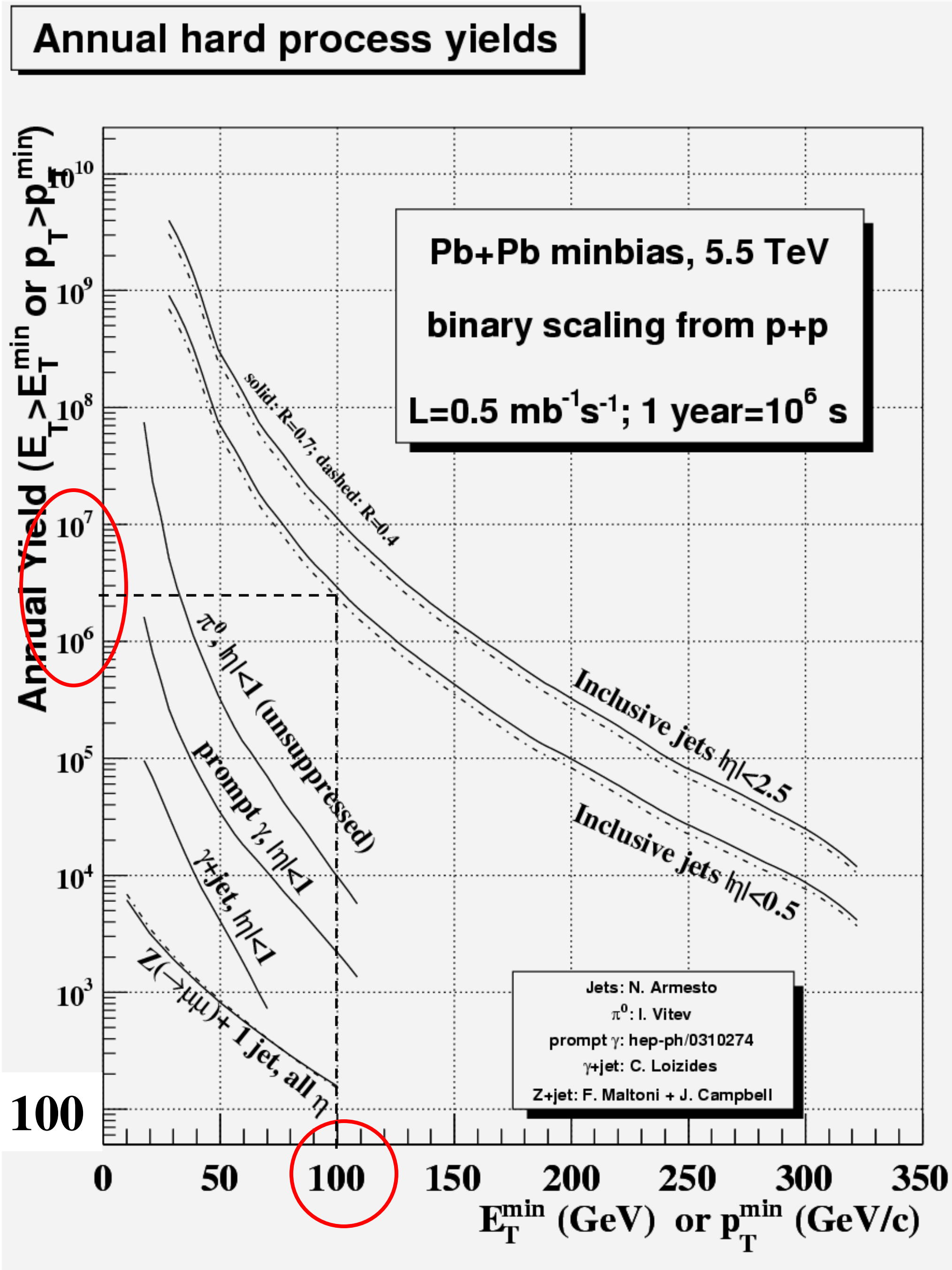
Study the properties of the QCD dense medium through **modifications of the jet structure** due to the parton energy losses (**jet quenching**):

- **Decrease of particles with high z, increase of particles with low z**
- **Broadening of the momentum distribution perpendicular to jet axis**

$$z = \frac{p_T}{E_T^{jet}}$$

Jet rates at the LHC

- **Copious production**!! Several jets per central PbPb collisions for $E_T > 20$ GeV
- Huge jet statistics for E_T~100 GeV
- Multi-jet production per event extends to ~ 20 GeV



Jet energy domain

2 GeV | 20 GeV | 100 GeV | 200 GeV

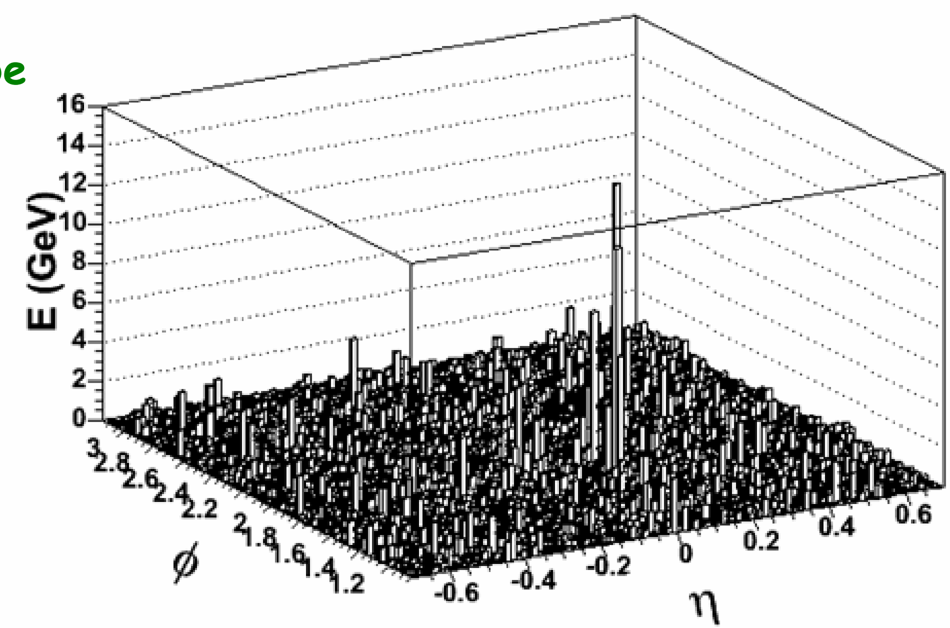
Mini-Jets 100/event | 1/event | 100k/month

No jet reconstruction, but only correlation studies (as at RHIC)
Limit is given by underlying event

Reconstructed Jets event-by-event well distinguishable objects

Full reconstruction of hadronic jets, even with the huge background energy from the underlying event, starts to be possible for jets with E> 50 GeV

Example :
100 GeV jet +
underlying event



ALICE detectors for jet identification

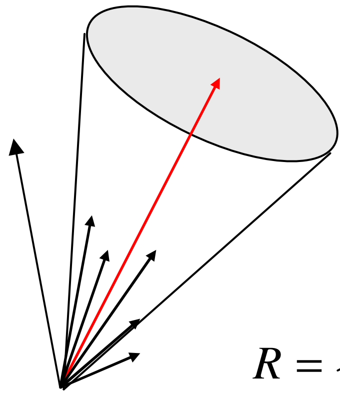
- ***Measurement of Jet Energy***
  - In the present configuration ALICE measures only charged particles with its Central Tracking Detectors

    (and electromagnetic energy in the PHOS)

  - The proposed Large EM Calorimeter (EMCal) would provide a significant performance improvement
    - E_T measured with reduced bias and improved resolution
    - Better definition of the fragmentation function: p_t/E_T
    - Larger p_t reach for the study of the fragmentation of the jet recoiling from a photon and photon-photon correlations
    - Excellent high p_t electrons identification for the study of heavy quark jets
    - Improved high E_T jet trigger

- ***Measurement of Jet Structure*** is very important
  - Requires good momentum analysis from ~ 1 GeV/c to ~ 100 GeV/c
  - ALICE excels in this domain

Jet reconstruction in ALICE



$$R = \sqrt{\Delta\eta^2 + \Delta\varphi^2}$$

In **pp-collisions**

jets: excess of transverse energy within a typical cone of R = 1

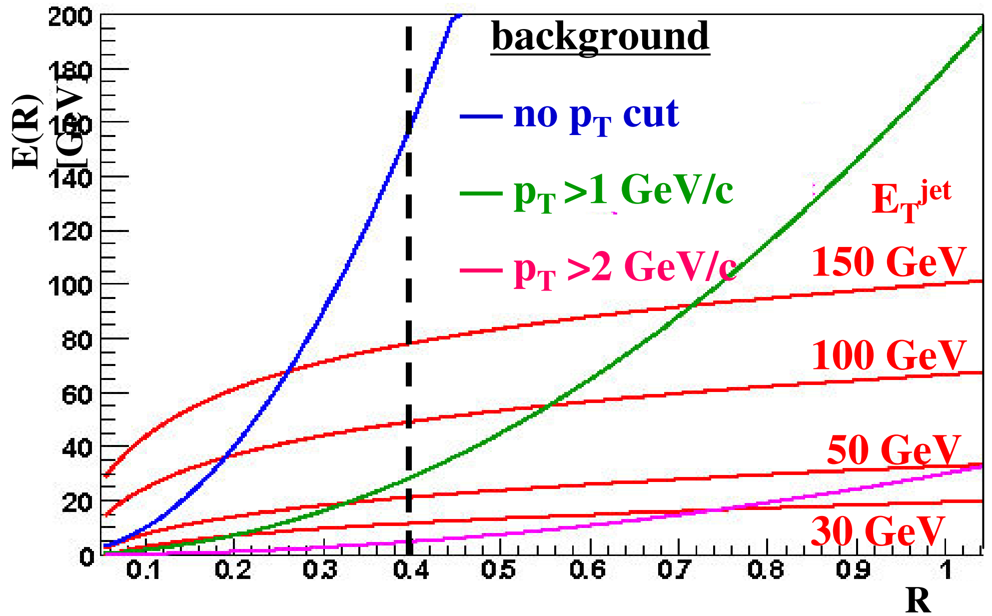
Main limitations in **heavy-ion collisions**:

- **Background energy (up to 2 TeV in a cone-size R=1)**
- **Background energy fluctuations**

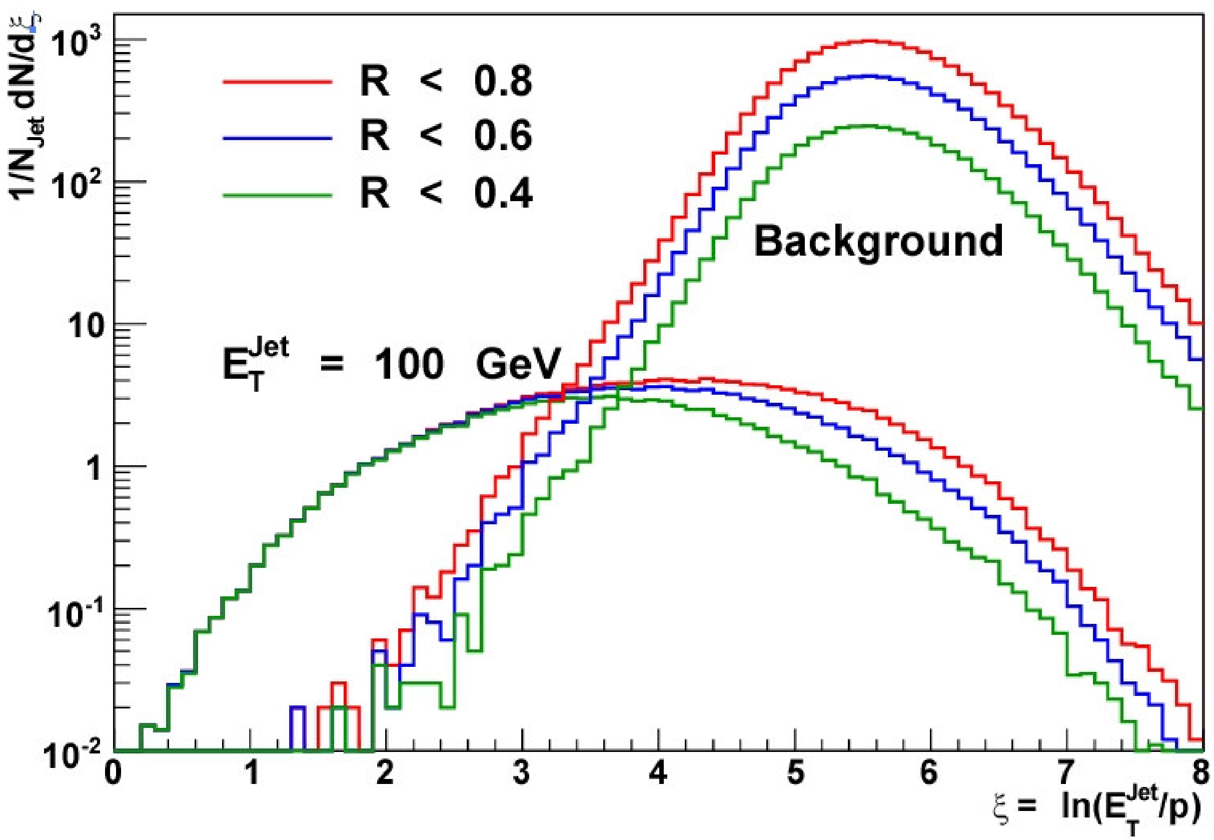
Background energy in a cone of size R is $\sim R^2$ (and background fluctuations $\sim R$).

They can be reduced by:

- **reducing the cone size** (**R = 0.3-0.4**)
- and with transverse momentum cut (p_T = 1-2 GeV/c)



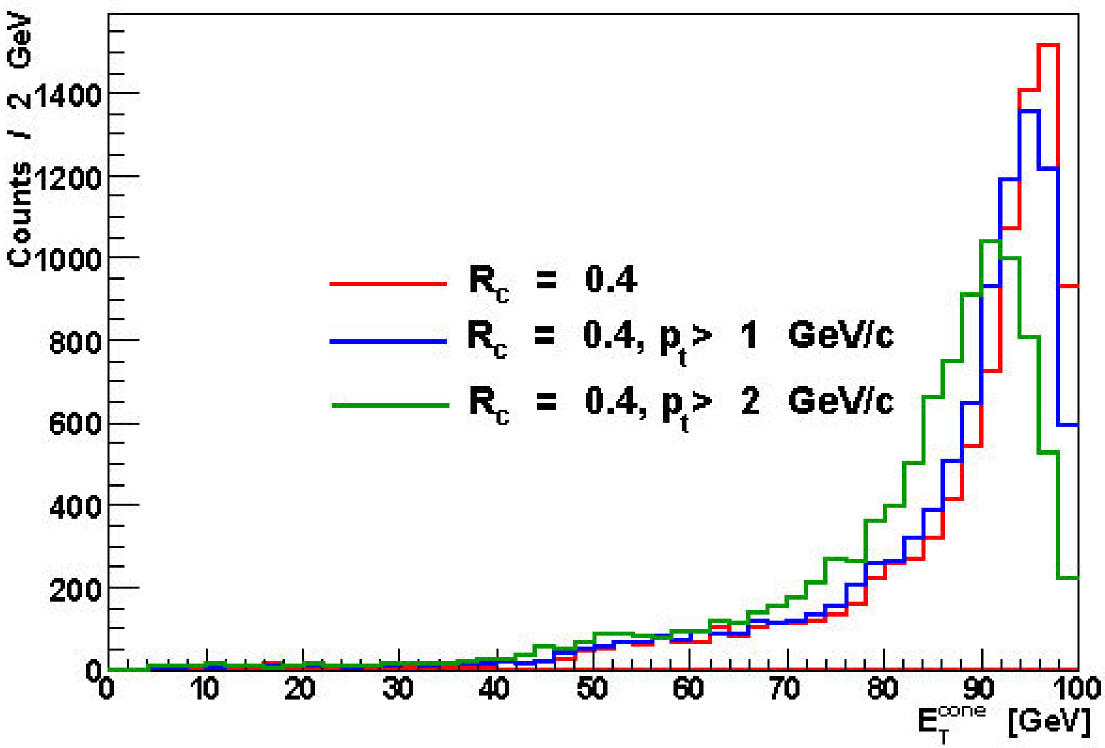
Background for jet structure observables: the hump-back plateau



S/B > 0.1 for ξ< 4 leading particle remnants p_t>1.8 GeV

S/B ~ 10^{-2} for 4 < ξ< 5 particles from medium-induced gluon radiation

Intrinsic jet reconstruction performance



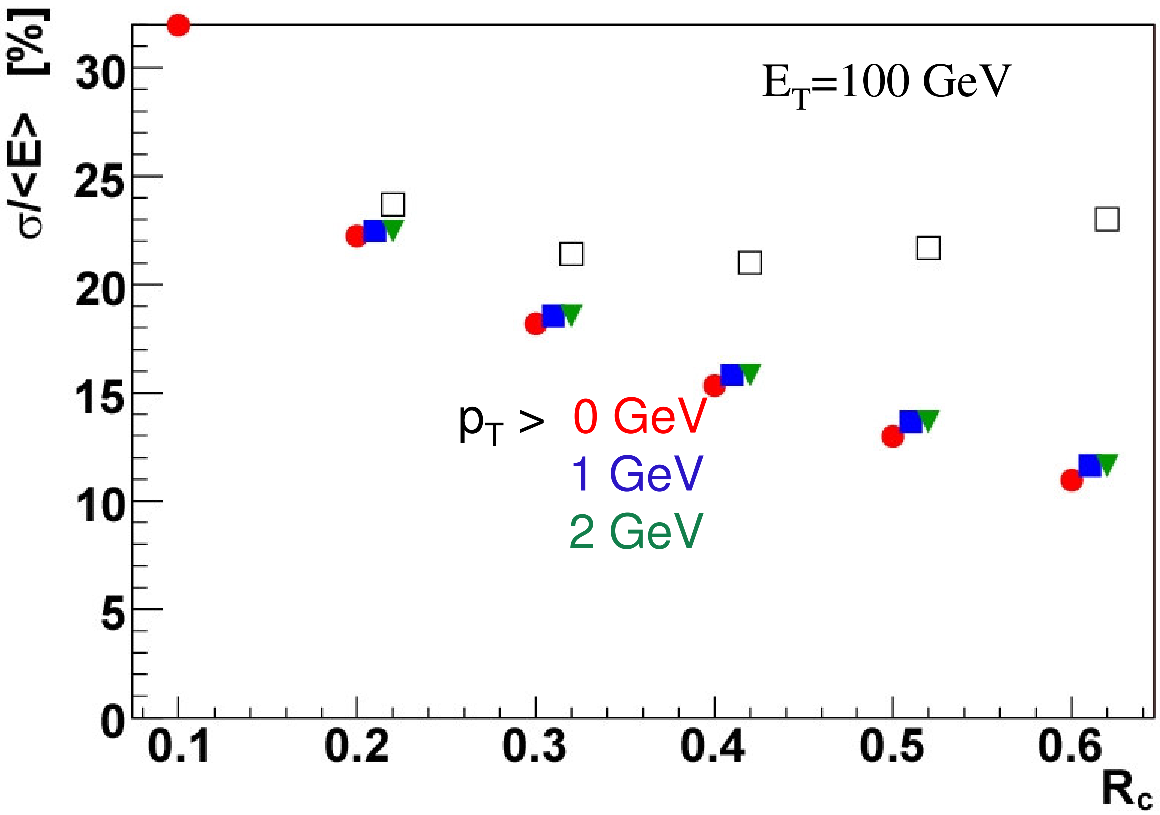
Out-of-cone fluctuations

E_T=100 GeV

The limited cone-size and p_t cuts (introduced to reduce background energy) lead to a low-energy tail in the spectra of reconstructed energy.
This tail is enhanced if detector effects (incomplete/no calorimetry) are included

Assuming an ideal detector and applying a p_t-cut of 2 GeV/c we expect, for a jet with E_T=100 GeV a reconstructed cone energy of 88 GeV with gaussian fluctuations of 10%

Energy resolution (for ideal calorimetry)



Background fluctuations added to signal fluctuations for the case p_t>1 GeV/c

Cone-size 0.3 < R< 0.5 : optimal limiting resolution $\Delta E_T/E_T$ ~22 %

Photon-tagged jets

Dominant processes:

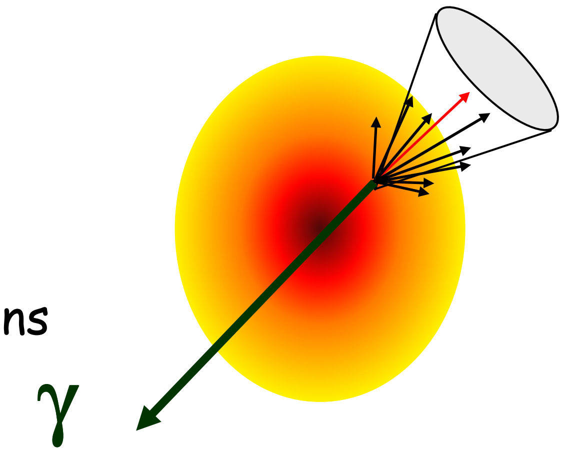
$g + q \rightarrow \gamma + q$ (Compton)

$q + \bar{q} \rightarrow \gamma + g$ (Annihilation)

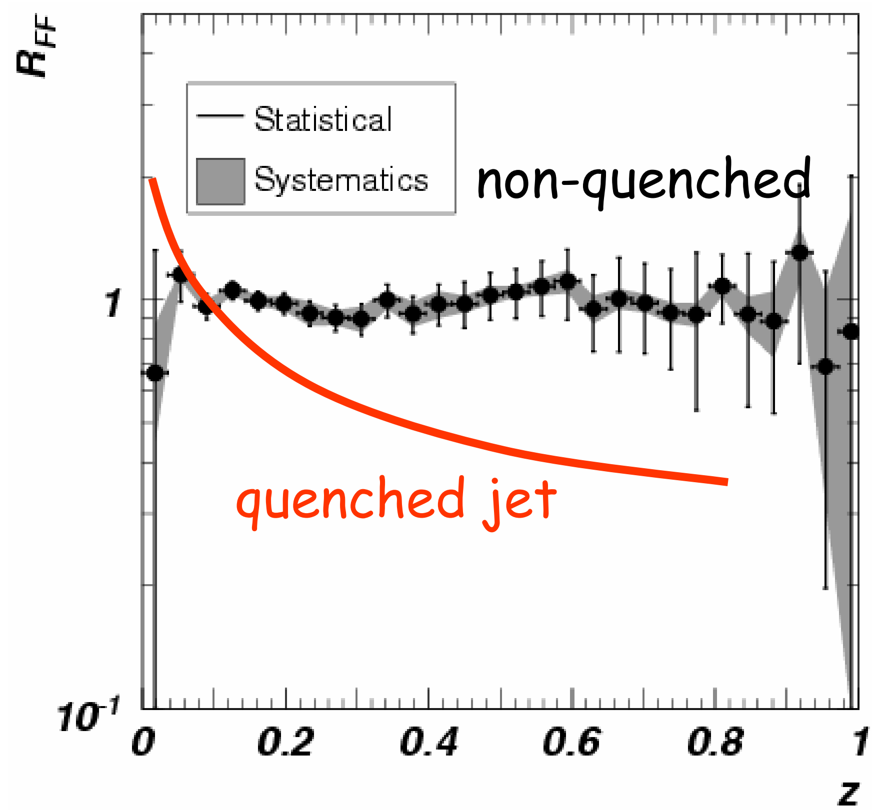
$p_T > 10$ GeV/c

γ-jet correlation

- $E_\gamma = E_{jet}$
- Opposite directions



- **γ energy provides independent measurement of jet energy**
- Drawback: low rate !!
- But... especially interesting in the intermediate range (tens of GeV) where jets are not identified
- Direct photons are not perturbed by the medium
- Parton in-medium-modification through the fragmentation function and study of the nuclear modification factor R_{FF}



Summary

- ALICE is well suited to measure **global event properties** and **identified hadron spectra** on a wide momentum range (with very low p_T cut-off) in Pb-Pb and pp collisions.
- Robust and efficient tracking for particles with momentum in the range 0.1 – 100 GeV/c
- Unique particle identification capabilities, for stable particles up to 50 GeV/c, for unstable up to 20 GeV/c
- The nature of the bulk and the influence of hard processes on its properties will be studied via **chemical composition, collective expansion, momentum correlations** and **event-by-event fluctuations**
- **Charm and beauty production** will be studied in the p_T range 0-20 GeV/c and in the pseudo-rapidity ranges $|\eta|<0.9$ and $2.5<\eta<4.0$
- High statistics of **J/Ψ** is expected in the muon and electronic channel
- **Upsilon family** will be studied for the first time in AA collisions
- ALICE will **reconstruct jets** in heavy ion collisions
  → study the properties of the dense created medium
- Furthermore, ALICE will identify also **prompt and thermal photons** → characterize initial stages of collision region

Credits

For fruitful discussions, and for figures and slides:

F. Antinori, A. Dainese, B. Hyppolite, C. Kuhn, L. Gaudichet, M. Lopez-Noriega, G. Martinez, M. Masera, M. Nardi, F. Prino, L. Ramello, E. Scomparin and Y. Schutz.